DOCUMENT RESUME

ED 239 583 IR 010 945

AUTHOR Spears, William D.
TITLE Processes of Skill Performance: A Foundation for the Design and Use of Training Equipment. Final Report, June 1978-July 1982.
INSTITUTION Seville Research Corp., Pensacola, Fla.
SPONS AGENCY Naval Training Equipment Center, Orlando, Fla.
REPORT NO NAVTRAEQUIPCEN-78-C-0113-4
PUB DATE Nov 83
CONTRACT N61339-78-C-0113
NOTE 167p.
PUB TYPE Information Analyses (070) -- Reports - Evaluative/Feasibility (142)

EDRS PRICE MF01/PC07 Plus Postage.
DESCRIPTORS *Cognitive Processes; *Design Requirements; *Educational Equipment; Learning Theories; Motivation; *Psychomotor Skills; Research Methodology; *Skill Analysis; *Skill Development; Task Analysis; Training Methods; Transfer of Training
IDENTIFIERS Goal Setting; Learning Curves

ABSTRACT

To lay a foundation for the design and effective use of low-cost, part-task and low-fidelity training devices, this report identifies dimensions of skill performance in terms of modern learning and behavior theory, and analyzes cognitive and motor skills as they relate to information processing. Cognitive processes discussed include task recognition; task comprehension; goal setting; planning performance; initiating, monitoring, and evaluating performance; stimulus encoding and elaboration; attentional processes; retention and retrieval of information; hierarchical schemata for discrimination and generalization; motivation; and skill integration and automatization. For motor skills, special attention is given to structural characteristics and movements; signal discrimination and generalization; roles of sensory modes and their interactions; and patterns of skill integration. Empirically-based concepts are used throughout to provide an operational means of manipulating variables during training, and examples are given of methods for empirically assessing the roles of various processes. Conclusions indicate that the analyses could readily be extrapolated to training technology in general and to the design of training devices in particular. Selected research topics illustrate what would be involved in the extrapolation. A 22-page reference list is provided. (Author/LMM)

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Technical Report NAVTRAEQUIPCEN 78-C-0113-4

# PROCESSES OF SKILL PERFORMANCE: A FOUNDATION FOR THE DESIGN AND USE OF TRAINING EQUIPMENT

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William D. Spears
Seville Training Systems Corporation
400 Plaza Building
Pensacola, Florida 32505

November 1983

Final Report June 1978 - July 1982

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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>NAVTRAEQUIPCEN 78-C-0113-4 | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>Processes of Skill Performance: A Foundation for the Design and Use of Training Equipment | | 5. TYPE OF REPORT & PERIOD COVERED<br>Final Report<br>June 1978 - July 1982 |
| | | 6. PERFORMING ORG. REPORT NUMBER<br>TR 82-06 |
| 7. AUTHOR(s)<br>William D. Spears | | 8. CONTRACT OR GRANT NUMBER(s)<br>N61339-78-C-0113 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Seville Training Systems Corporation<br>400 Plaza Building<br>Pensacola, Florida 32505 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS<br>PE 62757 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Naval Training Equipment Center<br>Orlando, Florida 32813 | | 12. REPORT DATE<br>November 1983<br>13. NUMBER OF PAGES<br>159 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED<br>15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

| | | | |
|---|---|---|---|
| Cognition | Motor skills | Transfer | Learning curves |
| Fidelity | Part-task training | Cognitive skills | Long-term memory |
| Information processing | Skill analysis | Cue development | Motivation |
| Learning theory | Skill training | Goal setting | Perception |
| Memory | Training | Learning | Retention |

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose was to lay a foundation for the design of low-cost training devices through an analysis of skill performance. Cognitive motor skills are analyzed in terms of the processing of information. Cognitive processes involved in both types of skills include task recognition; task comprehension; goal setting; planning performance; initiating, monitoring, and regulating performance; stimulus encoding and elaboration; attentional processes; retention and retrieval of information; hierarchical schemata for discrimination and generalization; motivation; and skill integration and automatization. (continued)

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For motor skills, special attention is given to structural characteristics of movements; temporal characteristics of movements; signal discrimination and generalization; roles of sensory modes and their interactions; and patterns of skill integration. Empirically based concepts are used throughout to provide an operational means of manipulating variables during training, and examples are given of methods for empirically assessing the roles of various processes. It is concluded that the analyses could be readily extrapolated to a training technology in general and to the design of training devices in particular. Selected research topics illustrate what would be involved in the extrapolation.

# FOREWORD

As noted in the introduction (Section I), the purpose of the report is to lay a foundation for the design of low-cost training systems through an analysis of skill performance. The foundation is based on implications for training of the processing of information as viewed in modern learning theory. Much of the study is tutorial; however, the analyses are invaluable for building a data base of behavioral information from which principles for guidance in equipment design and use may be derived. The analyses contribute to this goal by providing extensive and insightful information to show how and why modern learning theory should replace the oudated learning theory that still guides skill training in most respects.

Because much of the treatment is theoretical, there is a need to relate it to basic applied concepts. Section II, Basic Behavioral Concepts, provides empirical conceptual tools for this purpose. The emphasis is descriptive rather than theoretical, and the concepts identified are inferences from observable aspects of behavior. For instance, in the subsection "Primitive" Concepts, the need to analyze the roles of feedback is discussed. Questions concerning the value of platform motion in flight simulators are used to illustrate the complexities of feedback in training. In the subsection Higher-Order Concepts, such matters as cue development, transfer of training, and interference are covered. These factors are represented as being fundamental to the development of transferable skills and are emphasized as the critical factors in the successful use of training devices. (This material sets the stage for further discussions of transfer of training in Section V.) Two additional concepts discussed at the end of Section II, skill robustness and hierarchical organization, provide bases for further understanding of skill mastery, task integration, and instructional conditions required for optimal transfer of learning.

Sections III and IV consider the dimensions of cognitive and motor skills that are amenable to training. The material becomes more theoretical in these sections but is interspersed with many practical rules which arise from theory. In Section III, Analysis of Cognitive Skills, the author stresses the need for cognitive task analysis so that training can be based on more than grossly generalized training principles which provide little guidance for particular training practices. Section IV, Analysis of Motor Skills, emphasizes aspects of motor performance such as the temporal characteristics of movements that must be accounted for if transfer is to be successful. Implications for low fidelity devices are illustrated. For example, functional characteristics of training devices should not foster rhythmic patterns of motor actions that are different from those necessary in operational equipment. In the subsection on organization of motor skills, three examples are presented which illustrate the feasibility of a systematic methodology for observing and quantifying skill integration.

Section V, Manifestation of Transfer in Training, presents empirical indicators of the nature and amount of transfer of device training to operational equipment and situations. It also illustrates how the indicators

can reflect processes and effects of training in terms of the analyses in Sections III and IV. Four empirical indicators are described as parameters of performance curves that can be readily quantified. These parameters are beginning level, asymptotic level, rate of learning, and an inflection point which is a derivative of learning rate. Included is a discussion of the significance of each parameter for studies of transfer in applied settings. Measures of the four parameters require the fitting of curves to learning and transfer data. Examples are taken from actual field studies. They illustrate how we may miss the significance of data because data points alone may produce a misleading picture. As pointed out by Dr. Spears, the pattern of data shown by curve fitting may well say more than the data points per se can reveal.

The last section (VI) concludes that a training technology based on human performance can be derived for existing knowledge. Three research topics are discussed that illustrate individual research questions and programmatic efforts related to the role of the earlier analyses in applied training.

As stated, the primary purpose of the report was to provide a foundation for the design of low-cost training devices. However, the extensive analyses of skill performance necessary for achieving this goal also provides a foundation for training design in general. Although largely theoretical in development, the focus is nevertheless on aspects of modern learning theory that can be utilized directly when planning training, and without having to follow a theoretical system as such.

The report can best be used in its present form by personnel who are familiar with the process of translating behavioral information into training design specifications. This translation process would be facilitated through development of a method for performing learning analyses as described in the report. Development of this method would be high priority for further research efforts. A second research priority is to develop an efficient method for using the learning analyses to specify the design of instructional features that should be included in a particular training system.

A S Blaiwes

ARTHUR S. BLAIWES
Scientific Officer

# PREFACE

This report documents a study of training considerations underlying the design and effective use of part-task and low-fidelity training devices. The study was conducted under Naval Training Equipment Center Contract No. N61339-78-C-0113. Mr. William B. Boney served as the initial technical monitor for the contract. Dr. Arthur S. Blaiwes was the initiator and technical monitor of the study described in this report. Dr. Paul W. Caro was the Project Director for Seville.

The author is grateful for the support provided by Dr. Caro during the preparation of the report and for his insightful suggestions regarding its presentation. Thanks are also due for helpful comments by Mr. Joseph A. Puig of NAVTRAEQUIPCEN, Dr. Donald P. Foshee of Valdosta State College and Dr. James G. Greeno of the University of Pittsburg. Dr. Foshee and Mr. Puig reviewed all sections of the report, and Dr. Greeno's special contribution was for the section on analysis of cognitive skills. The expression of gratitude is not to suggest, however, that the reviewers endorse all statements in the report.

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# SECTION I

## INTRODUCTION AND APPROACH

The purpose of this report is to identify dimensions of skill performance in terms of modern learning and behavior theory. In doing so, it completes the first step of efforts to develop rationales for the design and use of part-task and low-fidelity training devices. The report is long because there is so much known now about skill performance that needs to be brought to the fore, knowledge that somehow has not been incorporated into formal treatments of skill learning in applied contexts. Thus it is necessary to delineate factors affecting, and the processes involved in, behavior that are considered only intuitively, if at all, by those who design training programs and related equipment. While the report does not do full justice to details of the processes involved, it seeks to identify those of critical importance which are also amenable to training.

Skill training in military contexts has not progressed significantly beyond the insightful, but seriously inadequate, formulations of Edward Lee Thorndike in the first third of this century. Thorndike built on concepts of learning that, in philosophical treatments, date back to ancient Greece and intuitively, probably back to primitive man prior to associationists such as Aristotle. What Thorndike--among many others--did was to express these age-old insights in terms of empirical relations. This was no mean achievement. One might even compare it to Galileo's empirical reduction of Aristotle's erroneous belief that heavy objects fall faster than light objects to a simple matter of momentum. A heavy falling object hits harder than a light one does not because it falls faster, but because the impact is the effect of its velocity, whatever it might be, multiplied by its mass.

Isaac Newton formulated Galileo's observations, and numerous others including his own, into three comprehensive laws. Thorndike, humbly and with no pretense of being psychology's Newton, proposed laws of learning. The law of frequency or practice stated simply that other things being equal, connections between stimuli and responses will increase in strength according to the number of times stimuli and responses occur together. A second law, the law of effect, stated that the connections will be strengthened if they are followed by a desirable result, or weakened if the outcome is undesirable. Later this law was qualified with respect to undesirable outcomes. It was also expanded to the law of spread of effect in order to accommodate gradients of desirable and undesirable outcomes.

As with Newton's laws of motion, Thorndike's simple statements of the relations involved seem vacuous upon assertion. Compare to Thorndike's law of practice Newton's first law, "the motion of an object will remain constant in velocity unless acted upon by an outside force." The trouble was that Thorndike's laws had nowhere near the deductive potential of Newton's, even though Thorndike's are frequently applied as if they were comprehensive. In fact, the most important, and complicated, aspect of learning and performance--meaning--was eventually subsumed by Thorndike under the superficial principle of "belongingness." Two things, like salt and pepper, are associated because they belong together.

Training as governed by Thorndikian conceptions has involved simply trainees' practicing a task with appropriate guidance, and observing the effects of their actions (feedback or knowledge of results). Intuitively we have attempted to account for belongingness by making practice "meaningful" because numerous experiments on learning and retention have shown that meaning enhances both. But what is meaning? How does it come about? What is its structure? Why and how does it enhance learning, retention, and performance? How can it be developed or provided? Are there many types and levels of meaning? Does it make a difference which types and levels are provided or developed during training? What should be known about individual trainees in order to optimize meaning?

The answers to these questions reveal the complexity of behavior that even laymen know must exist. But only during the last twenty years or so have answers been developed scientifically and systematically. These developments have not yet had an appreciable impact on military training. We still go at meaning like a layman--intuitively. The absence of modern thinking is especially noticeable in the design of training equipment and instructional programs for its use. The present study reviews the modern science of behavior and learning, and identifies factors and processes intuition cannot lead to, but upon which systematic training conceptions can be based.

The remaining parts of this section of the report discuss the background for the study and present a formal statement of purpose. Then a summary of the approach indicates the contents and organization of the remaining sections of the report.

## BACKGROUND

Military training is an expensive endeavor. An area where the expense has grown especially rapidly in recent years is the training of operator skills. The complexity of modern military equipment increasingly demands of operators a comparable complexity in skill knowledge as well as a high degree of precision in skill performance. Military readiness requires that these demands be met. Budgetary constraints require that the training of operators be as cost effective as possible.

Cost effectiveness can often be improved through use of relatively inexpensive training equipment to substitute for operational equipment during at least some phases of training. Also, simplifying training settings relative to the conditions surrounding operational performance often leads to significant cost reductions. Simulators have proved valuable in both of these respects. Those in use are generally less costly to procure than actual equipment, and even less costly to operate during training. They permit the simplification of training settings in that a classroom or teaching laboratory substitutes for an often unwieldly operational environment. There is also the advantage that simulators can be designed specifically for training. Actual equipment is necessarily designed for operational use, and hence usually lacks features and functional capabilities needed to capitalize on principles of training technology. Furthermore, skills can be taught safely with simulators that would involve danger to the student (or equipment) if actual equipment were used.

Even so, the complexity of much modern military equipment often requires considerable engineering and hardware costs even for devices to simulate the actual equipment. Therefore, a valid approach to reducing the costs of training devices and their use could lead to savings over and above those accruing from past substitutions of simulators for operational equipment.

Two cost-saving approaches that have been tried in the past several years are (1) the use of part-task trainers instead of full simulation trainers for portions of training; and (2) the reduction of fidelity of training devices to the physical characteristics of actual equipment. Both approaches have shown considerable promise. However, judging from current literature on training, both approaches lack a definitive guiding rationale for their conception, design, and use. Part-task and low-fidelity training devices are typically designed on an ad hoc, sometimes speculative, basis. The insights and analyses that guide the designs are not formulated sufficiently to guide the conception of such devices on a general basis. Furthermore, lacking formulation, the insights and analyses cannot identify issues of uncertainty (or of outright error) in device conception, design, and use that can be resolved only through research. Instead, a given device is evaluated in use, and accepted, modified, or rejected according to the outcome. While those responsible for the evaluations often report insightful analyses of what is effective and ineffective in devices and their use, these analyses, too, are ad hoc in that they apply primarily to the particular devices studied. As a result, little progress has been made toward a general formulation of rationales for part-task and low-fidelity trainers. There is even less progress toward identifying research issues which, once resolved, could remove uncertainties regarding such equipment on a general basis.

## STATEMENT OF PURPOSE

As stated, there is a need to develop rationales for the conception, design, and use of part-task and low-fidelity training devices. It is also important to identify gaps in our knowledge regarding skill training that, once removed through subsequent research, would ensure effective and efficient use of devices of these sorts. To accomplish these goals, it will be necessary to reformulate training issues in terms of modern conceptions of learning. Reformulation is dictated by the fact that the training of complex skills is almost universally conceived within a Thorndikian framework. There is little emphasis on information processing, the locus of all skill performance.

The first step toward achieving these goals, which is documented in this report, identified the learning and other behavioral concepts needed to analyze training issues of concern, and developed analyses on which the reformulation can be based. Future efforts will be required to derive rationales for low-cost training devices and identify research issues that should be clarified.

## APPROACH

The discussion that follows describes the approach employed during the first step for identifying learning and behavioral issues of concern, and for analyses of cognitive and motor skills.

ORIENTATION. The orientation of the approach follows the reasoning of Caro, Shelnutt, and Spears (1981) and Prophet, Shelnutt, and Spears (1981) with regard to the need for learning analyses to guide the design of training and training equipment. A contrast of learning analyses with task analyses, and with the Interservice Procedures for Instructional Systems Development (U.S. Navy, 1975), commonly referred to as ISD, will clarify what is involved in learning analyses. Task analyses focus on objective characteristics of what is done and accomplished during skill performance: the objective events that "cue" the initiation of an action, a description of what is to be done (task elements) in terms of objectives to be accomplished, and criteria for successful completion of an action. Building on task analyses, ISD prescribes ways to relate the various tasks and conditions for performance to instruction and instructional equipment.

In contrast, learning analyses begin with what is later described as cognitive task analyses. The intent is to identify the content and organization of skill knowledge, and to track the processing of information during skill performance. As will be clearly evident in Sections III and IV, the cognitive representations of skills and their performance introduce considerations for teaching discriminations and generalizations, and for avoiding or exploiting interference, that cannot even be anticipated in usual task and ISD analyses. Hence, building on cognitive task analyses, learning analyses relate training procedures to the locus of skill competence, the processing of information by the performer.

The complexity of information processing, of the mediational components and their roles, is precisely what is ignored in most formal analyses of the training of complex skills. It is not much of an exaggeration to say that skill performance is viewed only in terms of the objective descriptions obtained through task analyses. In describing what is to be done and when, task performance itself is supposedly described. "What is done and when" identifies the goal of skill training, not the process of skill performance, and even less the process of skill acquisition. A computer can be programmed to provide a set of printouts following specific inputs. But the printouts and inputs are not the program--the process--whereby the desired results are obtained. Neither do printouts and inputs explain how to program the computer, how to "train" it to perform as desired. Pushing the analogy one step further, "debugging" inadequate skill performance, like debugging a computer program, requires an understanding of the process whereby end performance obtains.

Analyses of the process of skill performance and acquisition require conceptual tools. For training purposes, the tools should be well grounded empirically, and they should provide "handles" for grasping issues and guidance for their resolution. Further, from empirical and theoretical analyses, the conceptual tools should represent components of, or at least contribute to, the schematic reconstruction of the process of skill performance.

It is doubtful that enough is known at present to support a comprehensive reconstruction (model) of complex skills. At any rate, no one has yet come up with one. Nevertheless, there are some excellent tentative models of cognitive behavior. Also, quite a bit is known about basic behavioral processes that play significant roles in all skill performance, and in a number of

instances the knowledge encompasses at least the broad nature of the roles. With the safeguard of staying close to empirical data, it should be possible to attain a level of integration of this knowledge that will be valid for present purposes, i.e., developing rationales for the conception, design, and use of part-task and low-fidelity training devices. However, there are serious gaps in the empirical support needed for many integrations. Until these gaps are closed, it will be necessary to resort to hypothesis and theory somewhat more often than might be desired.

In this connection, the efforts leading to this report have concentrated on laboratory and related theoretical research. Studies of these types are most likely to identify relevant analytic concepts and their implications for skill training in general. The intent is to establish a conceptual framework, based on fundamental issues in skill performance, that could help structure analyses of training for particular applied skills. As a result, little of the literature cited in this report concerned applied studies of training. Such studies will, of course, be a concern when deriving principles to guide equipment design and use.

METHOD. The method employed in the conduct of the efforts leading to this report can best be described through discussions of the tasks that were completed and their interrelations. In this regard, all subsequent sections of this report address method as they fulfill the several tasks. An overview of the tasks follows:

Identification of basic behavioral concepts. This task was the selection and justification of the conceptual "tools" referred to earlier. The concepts are defined in Section II, and their value as analytic and descriptive tools is illustrated.

Analysis of cognitive skills. The analysis of cognitive skills, presented in Section III, identifies dimensions of performance that are primarily cognitive in nature. The analysis is in general enough terms to cover a variety of tasks representing a wide range of military job specialties. "General" does not mean "vague," however. The thrust is to identify and explain dimensions of task performance that apply to all skills, and in a manner that can focus the analysis of any particular skill. Emphasis is on the roles of the basic behavioral processes that, logically, must be accounted for. With our present empirical knowledge regarding the basic processes, the kinds and levels of information to be sought in examining individual skills can be identified.

Analysis of motor skills. Section IV extends the analysis in Section III to motor performance. Because cognitive processes permeate motor skills, material in Section III is pertinent. In addition, special issues related to perception, coordinated movements, etc. are considered.

Analysis of manifestations of transfer. Transfer as a basic descriptive concept is discussed at length in Section II. However, that treatment does not go beyond traditional conceptions of the phenomenon as a product of training. As will be seen, transfer as a process permeates all cognitive and motor behavior, including the learning thereof. For that reason, empirical manifestations of transfer are indications of the kinds of processes that were

involved during skill acquisition. Accordingly, Section V examines quantitative manifestations of transfer in published training data, and illustrates the kinds of interpretations that can be made, depending on the measures obtained.

Summarization of value of analyses for training and training research. The intent in this task, discussed in Section VI, is to assess the analyses in Sections III-V for training purposes, and to point to significant questions that should be resolved through research. Examples of training implications appear throughout Sections II-V, so the assessment of the training potential of the analyses is general in nature. Three research efforts are discussed. These efforts are illustrative only, but each has profound implications for device training in general.

These five sections present the results of the present effort. The analyses of skills appearing in Sections III and IV identify performance variables whose development and integration comprise the goals of skill training. The empirically based conceptual tools presented in Section II, and elaborated in later sections, can provide for the manipulation of information processing during training. Section V explains how results of training can be evaluated empirically. The illustrative research topics discussed briefly in Section VI adopt a strategy for answering questions that can benefit the design of training programs and procedures for a wide variety of tasks.

## SECTION II

## BASIC BEHAVIORAL CONCEPTS

Modern cognitive psychology is rich in conceptions but lacking in an operational language that can guide manipulations of training conditions. In fact, only very recently has learning as opposed to performance of skills been addressed to any great extent. The purpose of this section is to present and illustrate concepts that comprise a set of operational tools for guiding the design of training conditions. The concepts all refer to aspects of information processing, and all fill mediational roles. As treated in this section, the concepts are descriptive and empirical in nature. That is, the phenomena they identify are immediate inferences from observable aspects of behavior.

It is necessary to emphasize at this stage the descriptive nature and empirical manifestations of these concepts so as to avoid unnecessary entanglements with theoretical conceptions. Theory will be needed later. But first, it is well to identify behavioral phenomena that theory must build upon and/or explain. Also, it is likely in many instances that, given a wise choice of basic empirical concepts, fruitful analyses of training issues (structure of skills, training design, etc.) need focus only on these observable characteristics and not resort to theory. This is not to say that theories are of no value. A valid theory with an operational language is the most practical intellectual device known. Rather, at the present stage of theory development in learning, especially in psychomotor areas, theories are severely limited both in general validity and in operational language.

There is a crude ordering of the basic concepts discussed below. Some, such as discrimination, generalization, feedback, and set are more or less "primitive" concepts behaviorally. That is, they cannot be reduced to more fundamental concepts without going into physiology. Other concepts such as cue development, learning set, transfer, and interference, which as separate phenomena are immediately inferable from behavior, can be conceived in terms of the more primitive concepts. "Transfer," for example, denotes generalized discriminations, regardless of how the discriminations are processed or the mechanisms of generalization.

In addition, two concepts, skill "robustness" and hierarchical organization, are discussed at the end of this section. These are not learning concepts in the way those mentioned earlier are. However, they do denote aspects of behavior and underlying processes whose empirical characteristics need careful examination. In the case of skill robustness, this phenomenon is basic to the transfer of device training to operational equipment; and though it is redundant in relation to other concepts discussed, it sometimes helps focus attention on certain skill characteristics more clearly and conveniently than other concepts do. The reason for including hierarchical organization in this section is to provide a basis for an empirical meaning of the concept. Usage of the term is often vague, with no clear grounds for identifying empirically the essential hierarchical characteristics specified by users of the term.

The usage herein of the various terms, as implied by the definitions provided, is largely consistent with traditional usage in the psychology of learning. In a few instances, however, definitions are couched so as to emphasize characteristics of special concern that may not have been of particular interest to other users of the terms (e.g., defining hierarchical organization in terms of functional relations rather than levels). Furthermore, all terms are not neutral theoretically. For example, Gestalt psychologists would probably prefer "differentiation" to "discrimination," and "transposition" to "generalization" and "transfer." Admittedly, the writer's behavioristic and functional background led to a choice of terms common to these approaches to learning. Nevertheless, for the purposes of this section, all concepts discussed should be considered descriptive in the sense they refer to phenomena recognized by all theorists. To the extent it is necessary later to go beyond description, the emphasis will still be on empirical rather than theoretical analyses to the extent data are adequate for the purpose.

"PRIMITIVE" CONCEPTS

DISCRIMINATION. Discrimination and the next concept discussed, generalization, are the two most basic concepts in behavior. One would always respond the same way, or else in a truly random manner, if he could not tell the difference between one situation and another, and between one possible response and another. "Discrimination" denotes telling the difference in both instances. ("Generalization" refers to the fact that discriminations are repeatable as situations vary, and that they are not one-time occurrences.) Discriminations are essential components of all skills, and the development of proper cue and response discriminations is a requirement for successful skill training. In fact, as apparent in later sections, formulation of all the factors internal and external to the performer that govern these processes would be a comprehensive theory of skill performance.

Except for a current emphasis on attention and signal detection in cognitive psychology, basic discriminative processes per se have not been the object of study or of theorizing except for classical work on the origins and foundations of behavior. Perhaps the reason is that in the laboratory where theories are usually developed, most discriminations required in studies of complex behavior have already been thoroughly mastered (telling one word or nonsense syllable from another in verbal learning; the host of prior visual-motor discriminations required even to qualify as a subject for a tracking task). Furthermore, studies have focused on simple tasks in which the additional discriminations to be learned are also simple and clearly evident (word anticipation in serial verbal learning), or lumped together in a single measure (time on target in a tracking task). In addition, studies of complex skills, conducted mostly in applied settings, have largely ignored the development and refinement of the basic discriminations involved. Criteria for performance usually, and quite properly, have been indications of only grosser aspects of overall performance which are of practical interest.

The position taken here is that of Caro, Shelnutt, and Spears (1981): the complexities of military task requirements in constantly changing conditions, the precision of skill performance that must be maintained regardless of conditions, and the use of training devices with varying characteristics, all require a focus on essential cue and response discriminations. This is not to

say that tasks must be analyzed discrimination by discrimination, for they are numerous even in simple skills. Rather, we must concentrate on factors and conditions that affect classes of discriminations, their development, refinement, retention, adaptability, and, of course, sources of their disruption. For many purposes, it will be necessary only to know the nature or sensory mode of discriminations, plus how the nature and modes involved shift with training and habituation of performance. This knowledge, especially of shifts in roles, is not always easily come by. The shifts have been studied only to a limited extent. Furthermore, we know comparatively little about proprioception, especially that derived from kinesthetic discriminations. Nevertheless, the successful use of part-task and low-fidelity devices will require the acquisition of skills that transcend--or in terms discussed later, are robust to--varying degrees of distortions in cues, responses, and conditions for performance. Ultimately, it is the discriminations of cues and responses that must be robust.

GENERALIZATION. "Generalization" refers to the extension of cue-response associations across time and situations. The term will be used in its common empirical sense to refer to the functional equivalence of stimuli (or individual cues), or of responses, across conditions of and contexts for performance. The term necessarily implies at least a gross discrimination of a stimulus or a response, or both. Thus, it is necessary to distinguish between "stimulus (or cue) generalization" and "response generalization." The former term refers to the functional equivalence of stimuli, that is, to the capacity of ostensibly varying or entirely different stimuli to evoke the same response. Similarly, "response generalization" denotes the functional equivalence of ostensibly varying or different responses that are made to a single stimulus.[1]

As explained in the introduction to this section, generalization is not to be viewed only in terms of stimulus-response psychology. Such a restricted view would destroy much of the value of the term for descriptive purposes. It would limit "functional equivalence" to a degree of physical similarity, which is fully descriptive of generalization only in laboratory situations in which subjects (usually animals) have no backlog of applicable experience to provide generalized meaning to stimuli and responses. Thus, their physical differences notwithstanding, a light and a buzzer are not only similar, they are functionally identical if they evoke equivalent responses; and, as Gestalt psychologists pointed out years ago, pressing a lever using the left hand, right hand, or even the elbow, is all the same if they fulfill equally well the task requirements cued by a single stimulus. Going one step further, a

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[1]Defining response generalization in terms of functional equivalence of responses is a deliberate departure from practice in training psychology where generalization implies a qualitative difference among responses. The definition is nevertheless standard in experimental psychology, and it highlights the most serious (valid) criticism of the so-called "transfer surface" (Osgood, 1949). When different responses are functionally equivalent, the generalization does not necessarily lead to a loss in positive transfer; it may even enhance it. Also, interference processes do not always follow as a function of dissimilarity (Slamecka & Ceraso, 1960). Functional equivalence, not similarity, is the issue--see later discussion of transfer.

stimulus generated on a cathode ray tube (CRT) in a training device, and a mentally rehearsed response to it, can be functionally equivalent to, respectively, an instrument reading and a resulting actual control input in operational equipment. Equivalence requires only an understanding of what is involved to complete indicated actions.

The emphasis on generalized functional equivalence, as opposed to physical similarity, of stimuli or responses is consistent with what we know about complex behavior, especially in humans. For some reason, in practice we have nevertheless chosen restrictive stimulus-response similarity models for viewing issues of training device fidelity, recognizing all the while the severe limitations of the models for complex behavior. Perhaps the reason is the assumed lack of an analytic system, including an operational language, for rigorous conceptions of functional equivalence. Because of the lack, as scientists we have focused on physical similarity which can be measured more or less objectively.

But an analytic system is available for establishing functional equivalence of stimuli and responses. An illustration appears in the discussion of transfer later in this section. As will be seen, functional equivalence can be put on quite solid logical and empirical grounds.

One more point should be made regarding the concepts of stimulus and response generalization defined in terms of functional equivalence. It may appear that by defining these concepts in a way that makes them correspondent to obvious characteristics of behavior, problems relative to generalizations have been simplified. Such is not generally the case. Rather, the complications are placed where they belong--establishing and training for the cognitive processing that underlies functional equivalence. A significant advantage of clarifying the complications is that various aspects of generalization can be targeted for training. They can also be researched more systematically and efficiently.

FEEDBACK. "Feedback" denotes information, understandable by the performer, regarding the adequacy of a response or action. Whether arising from without or within the performer, feedback of some sort is necessary for the maintenance of skilled performance and for the progressive changes in training performance that lead to skilled actions.

The concept of feedback originated in control theory where negative feedback fills the role of a system regulator. That is, it functions as a servomechanism to initiate corrective reactions to incorrect system performance. The concept came into use in psychology largely through attempts to use control models to describe behavior (see discussion of closed-loop models in Section IV), but the concept was quickly adopted for more general use by some application-oriented psychologists who had become disenchanted with the classical law of effect and its successor, the principle of reinforcement. The value of the concept has been compromised nevertheless by equating it to reinforcement. Actually, feedback, as applicable to skill learning and performance, and reinforcement have little in common. In a Skinner box, for example, a reinforcer such as a food pellet is feedback only when the animal is being "shaped," for that is the only time it communicates to him

information regarding the adequacy of his actions. Once he is shaped, food pellets serve only as incentives.

Confusion of feedback with reinforcement is no problem in modern cognitive psychology, and it is becoming more and more clarified in psychomotor skills, at least in basic research. Training literature, however, is still rife with "principles" of feedback that actually apply only to reinforcement. It is necessary to maintain a careful distinction between these concepts. Further, it is necessary to distinguish among the different roles of feedback itself. For example, feedback as a servomechanism and feedback as "knowledge of results" (KR) follow quite different laws. KR can be equally effective over a wide range of delays in availability, or when presented in a variety of forms. In fact, Kulhavy and Anderson (1972) and Sturges (1969, 1972) have shown that delayed feedback actually enhances retention of some knowledge (see Section III). When in the role of a servomechanism, however, any perceptible delay of feedback can be devastating for some skills, and the forms of its presentation (e.g., particular sensory modes) are often severely restricted. Such differences in the roles of feedback can be critical for training with part-task and low-fidelity devices. For example, in later discussions it will be apparent that permissible delays in and forms of feedback are far more restricted for skills conforming to a "closed-loop" model than for skills that fit "open-loop" models.

Questions regarding the value of platform motion in flight simulators further illustrate the need to analyze the roles of feedback. In their reviews of research on the effects of platform motion, Gundry (1976) and Caro (1977) attempted to resolve discrepant research data by distinguishing between maneuver motion and disturbance motion. The former results from control inputs, and hence comprises feedback within the control loop. On the other hand, disturbance motion such as may arise from air turbulence or engine malfunctions is not actually feedback. It is an indication of the status of the aircraft relative to the flight environment. In other words, maneuver motion, either as a servomechanism or KR, is feedback--information regarding the adequacy of ongoing control inputs that can be used to monitor, fine-tune, and correct them. Disturbance motion is an external cue signifying the need for a new control input.

On the basis of previous research, both Gundry and Caro concluded that maneuver motion was not of general benefit in a flight simulator, at least for stable aircraft, because it duplicates feedback available from instruments and other visual displays. However, Gundry (1976) in his review identified a variety of effects of motion on pilot response, including a closer correspondence of high frequency, low amplitude movements between simulator and flight control manipulations than was the case with no platform motion. On this basis, Gundry felt that motion as accelerative cues might be beneficial when unstable aircraft are simulated because high frequency inputs are needed. Caro (1977) also felt that accelerative motion cues might help when simulating unstable aircraft; and in a later paper (Caro, 1979) he related the possible beneficial effects to the fact that reaction times are more rapid to motion than to visual cues. In this case, aircraft instability per se would be only a special case of the need for platform motion. As Caro (1979) pointed out, motion may also be valuable, for example, in correcting for torque-induced yaw when taxiing a helicopter.

It is apparent that the roles of feedback can be complex, and that how it should be provided in training devices depends on a number of factors related to its roles and alternative ways of providing it--visual cueing for maneuver motion, g seats for accelerative cueing, etc. (It is also apparent that the distinction made earlier between maneuver motion as feedback and disturbance motion as new information breaks down in some cases. Are the reactions of an unstable aircraft maneuver or disturbance motion, feedback or new signals?) The extent to which the functioning and roles of feedback must be analyzed to derive training principles is not yet clear. For the multidimensional cue-response systems of many complex skills, the roles of feedback appear to have hierarchical characteristics in which the interplay of feedback as servo-mechanisms and as KR is quite complicated (and poorly understood). Furthermore, the functioning and role of feedback for a given skill often change during skill acquisition. This is especially true when trainees must learn to recognize and interpret stimuli that only after practice become feedback cues (see Cue Development). Early in training, they may need augmentation of naturally occurring feedback so as to enhance discrimination of it; or, they may have to depend on artificial feedback provided by, say, visual cues, to guide the learning of proprioceptive cues such as the "feel" of a correct response. (This process would characterize learning of open-loop skills which, early in training, function as closed loops.)

Castellan (1977) raised still more questions regarding the operation of feedback, especially the lack of systematic effects on final performance levels. Again, the extent to which the functioning and roles of feedback must be analyzed for present purposes is not yet clear. The broader scope of the problem is evident in later discussions.

SET. "Set" refers to a predictable, transitory tendency to perceive, react, or otherwise respond in a certain way, given certain conditions. Sets are inferred from cue sensitivities, response consistencies, and manipulatable conditions that establish them. In the past, they have been a basis for explaining positive and negative (interfering) transfer, attention, and the effects of guidance on learning. Sets are implicit in all theories of cognition. Some current models of motor performance invoke this concept to overcome difficulties in explaining selective attention and response initiation. In other words, "set" has been and continues to be viewed as a basic mechanism in behavior. There have been numerous studies of how sets are established and how they affect behavior. Nevertheless, "set" continues to be a relatively primitive, i.e., nonreducible, term because its underlying nature is not known. It is an empirical reality nevertheless, and as such denotes manipulatable conditions that affect, and are affected by, learning. (See also "learning set.")

## HIGHER-ORDER CONCEPTS

CUE DEVELOPMENT. Cue development depends on three factors: (1) the acquisition of meanings for stimuli in the context of goal-oriented behavior; (2) the association of a class of responses appropriate to the context; and (3) the generalization of the stimulus meanings and associated responses across time and situations. In other words, a cue is more than just a meaningful stimulus. The meaning must include means-ends relations which call for adaptive actions. Recognition that a compass reading indicates an incorrect course

does not comprise a cue unless the pilot knows what to do about it, and can do it in any number of situations. Therefore, "cue development" refers to the acquisition of entire complexes of the three factors mentioned.

Cue development (and by implication, cue) was defined in this way to emphasize the complexity of this aspect of skill training. The simplicity of the compass example notwithstanding, cue development is a much more complex phenomenon than discussions of it in training literature might suggest. In fact, explaining what is involved in even the simple compass example would require analyses of cognitive processes that go far beyond the level of description. Failure to come to grips with these complexities has prevented an analysis of cued behavior needed for training in general, and device training in particular. In one attempt to show what is needed, Stark (1976) presented an informative discussion of visual cueing in aircraft and simulators in which the complexities involved were clearly recognized. However, in spite of a fairly sophisticated analysis of a problem involving cueing, Stark did not focus on information processing, the heart of cueing.

Cue development in general follows patterns of discrimination learning. Pertinent stimuli and their variations must be differentiated within the context of the goals of performance, and their implications for response selection and monitoring recognized (response discrimination). As cueing systems develop, individual stimuli and stimulus patterns may result in cues for the onset of an action, or provide bases for the feedback cues necessary to monitor the responses comprising the action. Depending on the complexity, including duration, of skill performance, the sequencing and timing of responses must be sensitive to often subtle variations in internal and external stimulus conditions, with timely differential responses available as changing conditions require.

Obviously, any purposive action above the level of a reflex involves complex generalized discriminative systems for cueing and responding. And if it were not for the fact that persons undergoing training have a life-long mastery of a variety of basic coordinated cueing systems at the outset, skill training would be a hopeless endeavor.

Because trainees start with a repertoire of mastered cueing systems, training designs have assumed in effect that, given enough opportunity to practice a skill under the right conditions, any qualified trainee will eventually develop the refinements and generalizations of existing cueing systems required for successful performance in the tasks being trained. Much more can and will be said. Furthermore, when training with a low-fidelity device or even a part-task trainer, "right conditions" become a major concern. For a given stimulus condition in actual equipment, and for a given response requirement, how might training be designed so as to help the trainee select the most appropriate, previously mastered behavioral systems on which to build? Also, what varieties of stimulus conditions and/or responses in a device might be used such that a skill learned in the device has the topological properties required for performance in actual equipment?

An example will help clarify these questions. A pilot trainee starts with a highly complex set of alternative cues for distance, and with well habituated systems for using them in various combinations. One wishes to design a

low-fidelity visual system for a flight simulator that will be adequate for cueing depth-related performance of certain tasks in the simulator, and for transferring the cue-response relations learned therein to performance in an aircraft. Of the various depth cues habitually used by a pilot trainee, linear perspective is not only an important cue, its essential topological property, convergence with distance, can be provided relatively easily in a simulator, say with a checkerboard ground scene (Stark, 1976). Insofar as skills learned using the checkerboard cues can be transferred without serious disruption to cues derived from apparent convergence of highways, power lines, vegetation patterns, etc., during flight, the simple visual scene will have served its purpose. Note that another habitual depth cue, apparent size of objects, could have been added to the simulated visual scene, although at some additional expense. The question is, what partial cues are needed in a simulator to ensure intact cue-response transfer when all cues are available in the aircraft?

The approach to device design has been to seek fidelity of cueing systems--highways, etc., rather than checkerboard patterns--compromising only as available technology and costs dictate. There is no question that fidelity is critical for some training; but it is not for other training, and we do not know in general what the difference is. Analyses of topological properties of cueing systems (see later discussion of transfer) would aid in identifying the difference.

LEARNING SET. As usually studied by functionalists during the first half of this century, sets as defined earlier were manipulatable states in subjects that could be altered either through instructions or by arrangements of experiences during learning. In either case, they governed attention, transfer, etc., as these latter variables affected performance on specific tasks. In this light, effects of sets are hardly profound enough to account for the pervasive influences of experience that result in a high degree of consistency of performance among a variety of tasks. Neither are the effects at a level of generality sufficient to explain how past experiences of a diverse nature can be selectively brought to bear on a novel problem. In other words, while sets obviously govern cue processing and response selection in specific situations, what controls the sets?

In this context, the answer is "learning sets." The term refers to a class of enduring phenomena that are characterized by consistency of performance across a variety of tasks, and by the selection of aspects of past experience that are to be brought to bear on even novel problems.[1] At the risk of over simplification, the difference between "set" as usually used and "learning set" is illustrated by the simple instruction, "think opposites." A subject so instructed, when presented the stimulus word "big," will likely respond "little" or "small." Had the instruction been "think synonyms," the response would have been "large" or "massive." The instructions induced sets in the older sense of the term, i.e., transitory states of readiness and information

[1] As the term "learning set" implies, laboratory study of these phenomena has focused on their cumulative effects on discrimination learning. For the same reason, they are often referred to as "discrimination learning sets" and "learning to learn."

processing that could be changed by a new instruction. But the predisposition to follow instructions, whatever they might be, is a learning set. Learning sets are thus generalized discrimination systems characterized by (1) high orders of consistent information processing, and (2) stability of functioning across time because of habituation. In this light, they are basic not only to transfer, but to retention and rapid relearning of "forgotten" skills. They can also introduce habitual modes of processing information that, due to their rigidity, interfere with adaptive learning and performance.

Harlow's (1949) review of experiments by him and his coworkers demonstrated the empirical reality of these higher order sets. Their significance for understanding complex behavior is evidenced by their incorporation into theories of cognitive processing (e.g., Ausubel, 1968; Gagné, 1962, 1965, 1968; Gagne & Paradise, 1961; Hunt, 1961; Mandler, 1962; Mayer, 1975; Postman, 1969; Travers, 1963). In fact, Wolfgang Köhler, the leading living proponent of Gestalt theory at the time, readily admitted that "insight"--the classical Gestalt explanation of problem solving and transfer--had been an inadequate concept, and that learning sets were likely the bases for insights (Köhler, 1959).

It is surprising that systematic use of the concept of learning set has not been greater than it has, at least in cognitive theories. The concept is neutral theoretically, well grounded empirically, and it is "ready-made" for a class of concepts discussed later: "nonspecific" transfer, "figural" transfer, and "far" transfer. But the analytic power of the concept goes far beyond these concepts of transfer. In 1820, Thomas Brown (1820/1965) called the British Empiricists to task for neglecting such a logically necessary aspect of association. As an empirical concept, learning sets are operational handles for conceptions of the role of past experience in behavior ranging from "formal discipline" explanations of transfer to John Dewey's logical analyses of experience and education. Although they often miss the empirical advantage of the concept, modern theories of cognition do generally incorporate concepts such as analogical schemata that are of the nature of learning sets.

On the other hand, theories of motor learning as a rule do not use this concept, nor in most instances even incorporate processes analogous to it. This omission might be less surprising than in the case of cognitive theories. First, unlike cognitive skills, motor skills seem to be task specific. That is, intertask performance of a motor nature has been found to correlate very low from task to task, which is not true for cognitive tasks. Second, learning sets involve processes at least partly, probably mostly, in the cognitive domain; and while modern theories of motor skills recognize fundamental roles for cognition in motor performance, including schemata, they do not yet specify the roles in a way that defines them clearly, much less a way that leads to an empirical (operational) language. Third, theories of motor functioning have been based mostly on data concerning simple skills, observed over a short period of time. Thus, as in the bulk of temporally limited studies of verbal learning, "set" has been a useful concept in motor learning and performance (e.g., for postural motions, Smith & Smith, 1966, p. 360; for monitoring skills, Summers, 1981); but "learning set" has not because, to be of value, a variety of skills must be learned by each subject, and over a longer period of time than that usually devoted to an experiment.

While these three reasons may explain why learning sets have not been of interest in theories and models of motor skills, they by no means imply that these phenomena have no role in the motor domain. As for the low intercorrelations of performance across motor tasks, low intercorrelations characterize cognitive performance too when the tasks are simple relative to the maturity and experience of the subjects, or when the ability range of the subjects has been severely restricted through the mode of their selection. The low correlations follow directly from the lack of variance in performance. No one knows the magnitude of intercorrelations that might be found in motor performance if, as has been done extensively for cognitive aptitudes, motor "problems" (tasks) covering a wide range of graded difficulty levels were presented to subjects of a wide range of ability levels. (Even so, Zavala, Locke, Van Cott, and Fleishman [1965] found sufficient intercorrelations among flight skills for a selected group--helicopter pilots--to justify elaborate factor analyses.) Judging from common ostensible differences in general athletic ability alone, there must be a level of consistent processing of motor performance that transcends movement and manipulative skills specific to individual tasks. Learning sets may not be the critical mechanisms in the higher order processing, but they cannot be dismissed summarily. Nor, as has been the tendency, should possible intercorrelations among complex skills be ignored just because low intercorrelations were found among simple skills. It is important to keep an open mind regarding the intercorrelation of complex skills, for there is too much at stake to ignore possible inter-skill relations. Not only must vertical and cross-skill transfer (see below) be accounted for, it must be understood for optimum training.

The probable value of learning sets as explanatory concepts in motor performance is more readily apparent in other areas. For example, "schema" models of performance as explained in Section IV depend extensively on hierarchical cognitive processing. That is, higher levels of processing supposedly "assess" task requirements and govern the "selection" and "tailoring" of skill complexes to the requirements. In other words, schemata are highly generalized discrimination hierarchies; and depending on the situation, they can be bases for any manifestation of transfer.

At present, concepts of schemata are fairly well developed in cognitive theory but not in models of motor performance. They are assumed in motor performance because somehow we must recognize the versatility of skill utilization, and as explained later, hierarchical schemata overcome the limitations of "loop" models in this regard. However, there has been practically no research on the development of motor schemata, the most crucial issue for training. It may well be that what schema models offer to training can be realized by emphasizing the similarity of their presumed processing of information to that of the more empirical concept of learning set. By comparison, we know quite a bit about the development of learning sets and conditions governing their effects on behavior. By substituting a functional analysis of schematic processes for current speculations regarding their structure whether in cognitive or motor performance, schemata and their development can likely become tractable goals for training.

These examples illustrate how learning sets, as analytic tools, can be of considerable value. The examples do not exhaust possible uses of the concept, however. Spears, Sheppard, Roush, and Richetti (1981, Part I, p. 85-4f)

identified a variety of possible applications: Factors affecting training such as students' learning styles and their past experience should be at least partially reducible to parameters conceivable as learning sets; many cue parameters, including "similarity" relations in device fidelity, can certainly be so reduced; our knowledge of the development of learning sets should be, though it is not at present, exploited for designing training, scheduling practice, selecting sequences of tasks to be practiced, even defining intermediate standards for performance, as might be applicable, say, to part-task training. Spears et al. may have been a little overenthusiastic in that empirical reductions of these matters to learning sets have not yet been attempted. Nevertheless, just knowing that learning styles, for example, appear to exhibit all the characteristics of learning sets suggests immediately the difficulties--unto futility--that can be involved in designing training equipment, intentionally or unintentionally, that is efficient only for particular styles. Thoroughly habituated ways of processing information are difficult to change. (Try not to think opposites when so instructed.) A training device for which a given learning style is not appropriate may require more instruction to change the style in the learner than the effort and device are worth.

TRANSFER. Transfer of training is widely recognized as the critical factor in the successful use of training devices. The position taken here, and demonstrated later, is that transfer in some form is the critical factor in all training, including that with actual equipment, because it permeates all behavior. This position is implied in just about all modern cognitive theories, and it has been occasionally emphasized in applied training (e.g., Blaiwes, 1970). Nevertheless, it was not common in educational psychology 25 years ago (Spears, 1961).

With this view, it is difficult to separate descriptive uses of the term and those that go beyond immediate inferences from observations. Therefore, the discussion that follows does not adhere closely to a descriptive-explanatory dichotomy for the concept. Instead, the discussion focuses on certain points that will help clarify the uses of other descriptive terms. The treatment is traditional at this time, however. In Sections III and IV transfer assumes a more comprehensive role.

Transfer and Identical Elements. Because of their profound influence on thinking regarding device training, it is important at the outset to meet "identical elements" theories of transfer head-on. In doing so, perhaps these conceptions can be laid to rest insofar as the present effort is concerned, thus avoiding the necessity for redundant explanations and qualifications when analyzing skills.

Formulations of theories of common elements date to the turn of this century. The most sophisticated models, and the best grounded empirically, are those presented by Osgood (1949) and Houston (1964). It is necessary to consider only the former, for Houston's model is similar in conception. Extrapolating from numerous studies of facilitation and interference in (mostly) verbal learning, Osgood developed a three-dimensional "transfer surface" in which positive-negative transfer comprises a dependent dimension, with degree of stimulus similarity, and a gradation of response characteristics, comprising two independent dimensions. Generally, degree of positive transfer is

directly related to stimulus similarity and to response similarity, being maximum when learning and transfer stimuli and responses are identical, and tapering off as either transfer stimuli or responses are reduced in similarity. Unlike the stimulus dimension which is graded entirely as degree of similarity, the response dimension merges from "similar" through "dissimilar" and "opposition" to "antagonism." As a result, negative transfer is greater as learning and transfer stimuli increase in similarity, conjointly with responses becoming oppositional or antagonistic. If stimuli are totally dissimiliar or if responses are at some borderline point of dissimilarity, transfer is zero. That is, prior learning does not affect performance on a transfer task. Although somewhat oversimplified, this description of the transfer surface is adequate for present purposes. (It also goes as far as typical training conceptions of the model do.)

In past applications of the model to device training, similarity has been defined largely in terms of degree of physical correspondence of stimuli and of responses (and with no distinction between dissimilar responses and those which are oppositional or antagonistic). antagnostic). Hence physical fidelity of stimuli, and task fidelity of responses, have been emphasized in device design. (Task fidelity in this context requires both physical fidelity of manipulanda and functional fidelity of actual or simulated device operations.) It is widely recognized that a physical interpretation of similarity is unrealistically restrictive. Yet it is not uncommon in the literature on device training for an author to delineate shortcomings of the model, and then adopt it uncritically for analyses of device characteristics (e.g., Wheaton, Rose, Fingerman, Korotkin, & Holding, 1976).

Put bluntly, most criticisms of Osgood's model are not relevant. While even as a behavioristic conception the model has serious limitations--the failure to account adequately for the positive as opposed to negative role of response generalizations, for example--they do not reside in the presumed requirement of physical similarity. As Osgood illustrated (Osgood, 1952; Osgood, Suci, & Tannenbaum, 1957), "stimulus", "response", and the relation "similar" should be treated as undefined terms. (He did not call them this, but to the extent he utilized the model and its implications in the later writings, these were undefined terms in the logico-mathematical sense.) To apply the model, it is necessary to map one-to-one correspondences of undefined terms in the model onto the behavioral domain.

An excellent example of what is involved in a formal mapping is provided in the first chapter of The Measurement of Meaning (Osgood et al., 1957), although the process is not referred to as mapping there. For example, two "stimuli" (adjectives for Osgood et al.'s purpose) are "similar" (functionally equivalent in meaning) to the degree they evoke the same response (associations), have the same generalization and interference characteristics, etc. In the (transformed) language of the transfer surface, "when a sign or assign is conditioned to a mediator, it will also tend to elicit other mediators in proportion to their similarity to the original reaction and will tend to inhibit other mediators in proportion to the directness of their antagonism, or oppositeness, to the original reaction . . ." (Osgood et al., 1957, p. 14; italics in the original).

This statement, presented as a general law, obviously would make certain mediational processes--and functional equivalence of stimuli and responses--the focus of transfer. If a buzzer in a device, and an out-of-tolerance reading on an actual instrument, are associated with the same mediators, they will produce the same response; if the mediators are, in turn, associated with a class of functionally equivalent responses, any one of the responses may be produced, depending on circumstances. The general validity of Osgood et al.'s "law" may well be questioned. In fact, it appears naive in view of modern conceptions of cognitive similarity (cf. Ortony, 1979; Tversky, 1977; Tversky & Gati, 1982; see also Section III). The point is, however, that the originator of the transfer surface recognized the need to translate it into--map it onto--behavior, and in a way that the mapping conforms to specifiable empirical criteria.

One might still say that the transfer surface is an identical-elements model, with mediators now the elements. Furthermore, in the exchange, objectivity of stimulus elements and some response elements has been traded for unobservable internal events. While true, the exchange at least recognizes the complexity of human behavior, and it formally permits people to transfer learning as they are going to do anyway. (One is reminded here of Köhler's [1959] complaint that psychology is the only science that has made content secondary to methodology.) At any rate, there is an empirical safeguard in that specifiable relations in overt behavior must obtain.

It is not necessary for present purposes to take a stand for or against this formal extension of the transfer surface. The purposes are accomplished if the earlier use of "functional equivalence" in definitions of stimulus and response generalization is seen as justified; and if later analyses of mechanisms and dimensions of transfer (and interference) can be accomplished without undue dependence on physical characteristics of events except when they are critical (e.g., harmonic temporal phasing of negative feedback when it acts as a servomechanism in a coordinated harmonic action).

The Phenomenon of Transfer. To return to a more general discussion of transfer, the term will be used to imply a complex of generalized cue and response discriminations. Or stated differently, transfer results from a generalized discriminative system. Transfer is generalization; the difference in usage of the two terms depends only on the complexity, including patterning, of the generalizations involved. While a single term might be desirable, this distinction conforms to traditional usage of the terms. It also facilitates communication and analysis. For example, factors affecting transfer as a system of generalizations in all likelihood affect separate constituent generalizations differently. Thus, in discussing the effects of various training and equipment variables on transfer and generalization, the choice of terms, transfer or generalization, will help the reader recognize whether the effects under examination are to be considered gross in nature or specific to individual components of behavior.

The identification of transfer with generalization leads immediately to the inference that transfer permeates all complex behavior. In other words, it is the process whereby past experience influences subsequent behavior. While true, there could be a danger here of vitiating specific uses of the concept by extending it to a general theory of behavior. There is little

justification for such an extension, and it would be of no use for present purposes. The significant thing is that transfer is involved in all learning beyond the earliest conditioned reflexes. One learns by assimilating new information into existing behavioral and cognitive structures; by extending, refining, and adapting existing discrimination systems; by adapting existing response systems to new cues, and existing cue systems to new responses; etc. Obviously, the efficiency, and ultimate achievement, in learning depend on what the learner had to start with, and on additional foundations developed and elaborated during training.

These points are generally recognized; they have not been fully exploited, however. As Royer (1979) and Caro et al. (1981) explained, we have treated transfer primarily as a product of training, ignoring the fact that an understanding of transfer as a process of learning could improve both the training and the product.

Types of Transfer. Various authors have proposed distinctions among manifestations of transfer. While none of them are particularly good for analytic purposes, a brief review of the distinctions will reveal the range of phenomena that must be considered when analyses of skills are attempted. The product versus process distinction was just mentioned. A much older distinction is "specific" versus "nonspecific" transfer (McGeoch & Irion, 1952; Royer, 1979). Specific transfer is that across similar situations, for example, from a simulator to the operational equipment simulated. Nonspecific transfer occurs across dissimilar situations, and thus necessarily involves highly generalized discriminative systems, such as general principles that can be applied to a number of different situations. It is not restricted to principles, however. Nonspecific transfer would generally result from the establishment of any general learning set.

The distinction between "near" and "far" transfer (Mayer, 1975) also focuses on the situations involved. Near, like specific, transfer is that across highly similar situations. Far transfer fills a niche between near or specific transfer and nonspecific transfer. Far transfer situations are generally more different than those defining near transfer, yet there can be a commonality below the level of general principles as involved in nonspecific transfer. Far transfer would also be influenced by learning sets, however.

"Lateral" versus "vertical" transfer (Gagné, 1965) is a distinction very similar to the product-process dichotomy. Within the structure of learning hierarchies as viewed by Gagné, vertical transfer is the process whereby achievement of skills lower in the hierarchy facilitate the learning of higher skills. Vertical transfer is thus more restricted than process transfer which does not depend on a learning hierarchy. On the other hand, lateral transfer could encompass product transfer as well as nonspecific transfer.

The distinction between "literal" and "figural" transfer (Royer, 1979) focuses on the skills being transferred instead of the situations and contexts in which transfer occurs, thus opening up a new set of considerations. Literal transfer involves an intact set of skills (product) such as a standard routine for isolating a fault during troubleshooting. That is, the content of the behavior involved is essentially the same regardless of the occasion. Figural transfer involves flexible behavioral systems that can be combined and

recombined as conditions warrant, as would be required for fault isolation involving logical analyses of equipment functioning.

Although it is not apparent in this brief review, most of these conceptions of transfer were devised to fill particular needs related to the kinds of learning of concern to their originators. (Generally, the originators were concerned with cognitive learning.) It is interesting that, except for Gagne's vertical transfer, only the product-process distinction sought to highlight the role of transfer in the acquisition of learning. As will be demonstrated in Section III, all of these conceptions are actually quite crude. They derive from gross behavior, not its mechanisms.

INTERFERENCE. "Interference" refers to a relation among separate cue-response systems (or subsystems) such that the existence of one system results in degraded performance in another. Obviously, interference can be expected to the extent two concurrent cue-response systems are physically incompatible with each other. In skill performance, interference due to physical incompatibility can be avoided only by designing operational equipment and/or tasks in such a way that no two incompatible actions need occur at the same time. Hence, incompatibility is a concern primarily in analyses of human factors involved in equipment and task design. The present interest in interference is its effects on the performance of skills that are not intrinsically incompatible.

Interference among physically compatible skills is a major problem in training. Skills that do not lead to interference in expert performance may still pose major difficulties in acquisition and retention because they are interfering to nonexperts. As explained in Section III, interference is a very complicated phenomenon. It can arise at any of numerous stages of information processing, and it can be beneficial as well as disruptive in skill performance. But wherever it occurs, disruptive interference indicates inadequate discriminations, whether of cue interpretation, response selection and adaptation, preparatory sets, or any other mediational component of information processing. The faulty discriminations may be due to inadequate opportunities to learn (and make habitual) the discriminations in the first place; to overgeneralizations (negative transfer) of cues, responses, etc., of one skill that obscures unique aspects of another; or to internal and external conditions (anxiety, unexpected events, etc.) that result in reactions other than those involved in skill performance.

A lot of research has been done on the nature of interfering processes, their effects on performance and retention, ways to avoid and accommodate them, and how to remove them when originally interfering skills are to be integrated into a more comprehensive skill or time-shared performance. This research will not be reviewed here. Rather, the present discussion will highlight how knowledge of interference can aid in the design and use of part-task and low-fidelity training devices.

First, specific limitations of existing models of skill performance are perhaps best revealed by their failures to account for patterns of interference that have been well established empirically. Knowing these limitations as they apply to individual models will help avoid unwarranted extrapolations of the models to the design and use of training devices. Second, patterns of

interference that have been observed could help in topological mappings of cue-response systems across training devices and actual equipment, as discussed in connection with transfer. For example, to justify empirically a mapping of the transfer surface (Osgood, 1949) onto behavior, functional equivalences of interferences of cue-response systems must obtain.

Third, practice conditions that minimize interference can guide the selection of tasks for training with part-task devices. For example, two tasks that must eventually be performed together, such as flight control and communication with the ground, may be mutually interfering during acquisition. For many tasks, the interference can be reduced if one or both are first mastered separately to some minimum level before integrated practice is attempted. A fourth value of data regarding interference is closely related to the third. It is based on the fact that, as a general rule, tasks are less mutually interfering to the extent they depend on different modes of processing (visual versus aural feedback; verbal versus kinesthetic cueing; etc.). Thus, even though two tasks must eventually depend largely on the same modes, early joint practice of the tasks may be more efficient if practice conditions permit aural feedback for one task, for example, even though both depend ultimately on visual feedback.

A fifth, and major, value of previous research on interference derives from the relation of interference to retention and transfer. As for retention, the only comprehensive "theory" of forgetting--the inverse of retention--is an interference theory: things are forgotten, skills become degraded, etc., because, over time, subsequent or even previous learning and behavior competes with a given skill such that discriminations among skill-unique cues, responses, mediators, etc., become obscured. The difference between skill "degradation" and ostensible "forgetting" of the skill is thus seen as a matter of degree. As evident from studies of relearning, skills are never completely forgotten. They appear so because interference is at a level that observable response production is absent or at least highly erratic.

Negative transfer by definition results in interference. In fact, there have been occasional allusions to negative transfer as the "vehicle" for interference effects generally. However, as stated earlier, with our present level of knowledge there is nothing to be gained by making transfer a general theory of skill performance. In the present case, it is better to view skill degradation and forgetting as an obscuring of discriminations, and negative transfer as the direct competition of actions, all of which may have clear-cut discriminations. The fuzziness of this distinction notwithstanding, it does help focus training issues on empirically established effects of interference that relate specifically to retention or to negative transfer.

## ADDITIONAL CONCEPTS

SKILL ROBUSTNESS. "Robustness" as used here is a term borrowed from statistics. In statistics, it describes an analytic procedure whose validity is not noticeably affected by appreciable violations of assumptions underlying it. By extension, its use to describe skills (e.g., Thorpe, 1978) denotes the adaptability of skilled performance to a variety of situations in which cues have unaccustomed, even distorted, characteristics, and/or in which responses must change qualitatively or quantitatively to achieve a desired end. Thus,

skill robustness implies functional equivalence among a variety of stimuli and a variety of responses involved in performance.

As a descriptive term, "robustness" is especially useful for present purposes because it designates a class of skill characteristics (1) that should be a goal in all training, and (2) that are crucial to successful use of part-task, and especially low-fidelity, training devices. A person with robust skills would experience less interference and hence would have less of a retention problem, could apply the skills in a variety of ever changing situations, and could transition from one configuration of equipment to another (e.g., one type of aircraft to another type) with at most only temporary degradation of performance. As for training with certain low-cost devices, skill robustness ipso facto is necessary for transfer of training to actual equipment.

Prophet et al. (1981) pointed to the need to understand, and to train for, skill robustness. The present effort pursues both goals as they relate to device training. However, the concept has value for other purposes as well. For example, among the models of motor skill performance discussed in Section IV, the critical shortcoming of closed- and open-loop theories, and to some extent, "channel" theories, is their inability to account for skill robustness. Schematic models on the other hand address robustness directly. Skill robustness thus can be a basis for evaluating models of skills as guides for the design and use of part-task and low-fidelity devices. (The concept also helps focus analyses of skills as illustrated later.)

HIERARCHICAL ORGANIZATION. This term will refer to an organization of skills or of skill components which is defined by more or less rigid functional relations. Most models of cognitive skills make extensive use of hierarchical structures. They are much less common in motor theories.

Typically, hierarchical organization is conceived in terms of "levels," which in turn represent an order of inclusiveness or implication. For example, the ability to land an aircraft successfully includes, or implies, at least minimum skill in manipulating aircraft controls. Thus, landing an aircraft may be considered at a higher level in a hierarchy of flight skills than control manipulation.

There is an obvious difficulty in such an inference, and the problem illustrates the reason for the definition of hierarchical organization in terms of functional relations as given in the first sentence above. For example, motor skills, at least for certain sets of tasks, tend to be largely independent of each other. Strictly speaking, landing an aircraft implies competent control inputs only for those inputs involved in landing. It does not imply proper use of controls for other maneuvers.

The concept of skill hierarchy will be fruitful not only for understanding skill organization but for identifying separate tasks as candidates for part-task training. If a higher-order skill implies, i.e., requires, lower-order skills, the latter can be learned in a device that does not train the more comprehensive skill. However, it will be necessary to specify clearly the nature (and limits) not of levels but of functional relations that define hierarchical organizations. And aside from an immediate concern with part-task training, conceptions of hierarchical structures in models and other less

formal accounts of skill learning represent a variety of possible relations, some of which have nothing to do with levels or implications. It is important not to confuse various conceptions by lumping posited functional relations among skills and skill components together under a single set of relations such as "levels."

Gagné's (1965) learning hierarchies are a case in point. "Levels" are established to the extent that prior mastery of a given skill is a necessary condition for mastery of another skill, the latter being "higher" in the learning hierarchy. It is also assumed that, because of this relation, mastery of the lower skill must transfer in some way to the learning of the higher skill. Both functional relations may hold in fact for learning certain skills; but it can be misleading to consider the relation defined by a necessary learning sequence, and that defined by vertical transfer, as a level or even a unitary relation. In fact, undue emphasis on a unitary relation may restrict the applicability of a hierarchy so conceived. As Bergan (1980) stressed, there can be a necessary sequence in learning without vertical transfer, and there can be vertical transfer without a necessary learning sequence.

Hierarchical relations, especially in skill performance as opposed to learning, can be defined in a number of ways; and if hierarchical models are to be useful for analyzing tasks and training requirements, it will be important to focus on the particular relations involved. Schema models of skill performance posit a hierarchical structure of control that could be largely (but probably not completely) independent of learning sequence, and hence they open up possibilities for part-task training that might be excluded from a strict learning-sequence model. Schema models also imply lateral transfer that is in a direction reversed from the vertical transfer in Gagné's hierarchies. That is, higher "levels" of skills (analytic schema) mediate use of lower level skills (cue-response systems). (As lateral transfer, this conception is not necessarily at odds with Gagne's.) With the definition given earlier, still other sorts of hierarchies can be conceived, embracing sequential behavior, for example. If the performance of subtask A must precede subtask B, and B precede C, etc., there is an organizational relation involving sequence. Design for training such a series of task elements should allow for the sequential restrictions (and probable sequential cueing) so as to minimize problems of eventual task integration. From the standpoint of part-task training, a need for total-task integrity during training of sequential skills may be quite different from that for sets of subtasks that have no strict sequential relations.

In brief, it is necessary to recognize a number of defining relations for skill organization. In some instances, it may be helpful to view a model in terms of hierarchical organization whether or not the proponents of the model did so. (The reverse, of course, could also be true.) Also, sets, learning sets, and even feedback, exhibit relational characteristics that conform to hierarchical organization. Fortunately, there are a number of techniques, ranging from psychophysical scaling to cluster analysis, for defining the bases of hierarchical organization in empirical terms.

# SECTION III

## ANALYSIS OF COGNITIVE SKILLS

As with any other phenomena, cognitive skills can be analyzed in a number of ways. The guiding principle in choosing a particular analytic scheme is therefore to seek relations among variables pursuant to a purpose. Sir Arthur Eddington's typically picturesque example of an elephant sliding down a grassy slope makes the point vividly. How would a physicist describe it in the language of his science, a language constructed specifically for his purposes? "A mass of two tons moving along a plane inclined at sixty degrees" is about all he can say.

A serious problem in modern cognitive psychology is that there is at most a limited consensus regarding what is to be studied and hence an appropriate systematic language. In another picturesque example, Claxton (1980b) likened cognitive researchers to the inhabitants of thousands of little islands, representing different cultures, habits, and ways of talking about what they do. "Occasionally inhabitants of one island may spot their neighbors jumping up and down and issuing strange cries; but it makes no sense, so they ignore it" (p. 15).

Many differences in research objectives and language, and hence constructs, derive from metatheoretical preferences. There are neobehaviorists, neofunctionalists, neogestaltists, and neostructuralists. The first three of these groups have one thing in common, their metatheoretical differences notwithstanding. They concentrate on processes of cognition qua processes. On the other hand, neostructural approaches often reify agents to explain processes.

An example is the short-term memory (STM) versus short-term store (STS) terminology, or long-term memory (LTM) versus long-term store (LTS). As apparent later, STM and LTM can be defined operationally with no commitment regarding a fundamental distinction between the two. On the other hand, STS and LTS are hypothetical constructs that supposedly account for STM and LTM (Baddeley & Hitch, 1974). As with computers, "store" connotes a register--locus--that is integral to process. STS and LTS imply structurally distinct loci in the central nervous system; as causal agents, they supposedly engender memory processes that follow the different laws derivative of the loci. (Some writers refer to stores only metaphorically, however.)

The present purpose in analyzing cognitive skills is to lay a foundation for skill training, and especially for the design and use of part-task and low-fidelity devices. Training is a process and performance is a process. The former is to be designed so that variables, including equipment design, can be manipulated to develop the latter. A strict structural analysis, one that assumed the priority of memory stores over processes, for example, would be a roundabout way at best to reveal what can be done to change and develop performance. One would seek the characteristics of structures and their derivative laws. But to what purpose? Training cannot change structures nor their immutable laws.

As will be evident, strict structuralism, which seems to have peaked about ten years ago, is on the wane. But even assuming concepts such as "store" to be valid, present purposes dictate an analysis of cognition in terms of processes. Further, the processes selected should be capable of manipulation for training. For example, a supposed characteristic of STM, as a process as well as store, is a severe limitation on the number of elements that can be represented (remembered) at one time. Yet, there are numerous situations in which the limits are exceeded substantially. Theorists then speak of "chunking," or the combining of elements into chunks so that a chunk becomes an element, and the limits apply to the number of chunks. A training developer needs to know how to cause chunks to form, and in a manner that optimizes training. If no guidance can be given, then chunking has no value as a training concept and hence should be ignored in the present analysis.

As explained later, chunking can be a useful training concept, but only if one goes well beyond discussions of the notion as such in research literature. The choice of conceptual tools discussed in Section II was to provide for occasions such as this. Chunking can be manipulated through preparatory sets which draw on LTM, and trainees can learn to manipulate their own sets. ("Set" may well be a useful tool for dealing with a number of STM processes, including control of interference--see later discussion.)

Another example is the concept of schema, which in the abstract is the most useful explanatory construct in cognitive psychology. Schema-like processes govern all complex behavior, so developing appropriate schemata is a training goal of paramount importance. The trouble is, there is very little research on how schemata develop, let alone how to foster their growth. Most theorists who make major explanatory use of this concept live on one island, and those that talk of learning sets, for example, live on another. The primary reason for including "learning set" as a conceptual tool (Section II) was to gain a "handle" for the all-important concept of schemata. We know quite a bit about how to develop learning sets.

The present analysis of cognitive skills, then, is pursuant to a particular purpose: a foundation for skill training in general and for designing and using part-task and low-fidelity training devices in particular. The task for the psychologist who would design training programs and equipment is to sift the strange cries emanating from the many islands for insights into processes that can be manipulated for training. To do so requires an excursion into formal theories of cognition so as to clarify their concepts. Accordingly, preceding the analysis of cognitive skills appear brief summaries of the emergence of modern cognitive psychology, central concepts of information processing, and a section illustrating theoretical approaches to memory. Cognitive skills are then analyzed in terms of executive processes, short-term processes, long-term processes, and motivation.

## EMERGENCE OF MODERN COGNITIVE PSYCHOLOGY

Regardless of the degree of mechanization implied by a theoretical position, "cognitive skill" connotes more than overt stimulus-response (S-R) connections. There are mediational events between the occurrence of an input S and the resulting output R that are integral to the overall action. These events may be viewed as implicit S-R chains (e.g., subvocal speech) as in the

classical behaviorism of Watson (1919, 1930) or Guthrie (1935); as constructs anchored to physical stimuli and overt responses as in the neobehaviorism of Hull (1943) or Spence (1956); or as organismic (O) mental and physiological processes as in the functionalism of Carr (1925) or the S-O-R formulation of Woodworth and Schlosberg (1954).

However, throughout this century there have been theorists insisting that the mediational events are purely cognitive in nature and must be studied as such. That is, they are essentially mental--a physiological substratum notwithstanding--and they are manifestations of purposive, intelligent comprehension of the situations in which actions occur. The cognitive point of view was systematized in the past by Tolman (1932) and the Gestalt school (Koffka, 1935; Köhler, 1929/1947; Lewin, 1936). The cognitive theorists stressed that behaviorism, whether old or new, simply could not account for intelligent behavior. As it turned out, the cognitive theories of the first half of this century were not adequate for the job either (Hochberg, 1957; Miller, Galanter, & Pribram, 1960; see also Köhler, 1969, for discussion of fundamental brain activities underlying thought that occur outside of mental activity per se).

Beginning around 1960 there was a renewed interest in cognitive processes that resulted in their study becoming part of the mainstream of current psychology. Rather than being only critics of the behaviorism that dominated psychology in this country from 1930 to 1950, cognitive theorists began to play central roles in psychology's development. Some would date this renaissance to the publication of Miller, Galanter, and Pribram's (1960) Plans and the Structure of Behavior, a "subjective behaviorism" (Hilgard, 1980) that would derive behavior from a hierarchical structure of plans. In the transition, a neostructuralism has developed (Mandler, 1962). It has little in common with the structuralism of Wundt or Titchener, but it does rely on an updated nineteenth century methodology: the use of reaction times to "track" and identify mental operations (cf. Castellan & Restle, 1978; Chase, 1978; Estes, 1978b; Theios, 1973, 1977). Neostructuralism emerges when the operations are ascribed to "locations" in memory--working memory, short-term store, long-term store, etc. (see Bower, 1975, for an elaborate flow diagram of the perceptual-memory system).

Many writers eschew the structuralism, focusing instead on the mental operations as processes. And perhaps it is in this distinction, structure versus process (Estes, 1978b), that the most basic disagreements among today's cognitive theorists lie. "Process" theory appears to be an extension of neobehaviorism (e.g., Kendler & Kendler, 1975) or of functionalism (e.g., Postman, 1975). These theorists, including the modern neobehaviorists, emphasize mediational processes other than stimuli and responses; but they would conform to the approach of Woodworth and Schlosberg (1954) in having "a definite preference for objective data but no taboo against material obtained through introspection if it helps the psychologist to understand what the organism is doing in relation to the environment" (p. vii). Although it seems that neostructuralists would say the same thing, in practice they tend to go well beyond data, from readily inferred processes to mental agents whose reifications are questionable.

The structure-process distinction will arise several times in the discussions that follow. To avoid confusion, two different uses of "process"

should be clarified. One use is in the structural (i.e., structuralism) versus process approach to cognition just mentioned. The other use of "process" as in "information processing" is generic. It includes both structural and process approaches to cognition. The following discussion provides an overview of "information processing" in its most general sense.

## OVERVIEW OF INFORMATION PROCESSING

The use here of "information processing" (IP) departs somewhat from many current practices in that it includes even modern neobehavioristic conceptions of cognition. Although Estes (1978b) distinguished between "behavioral" and "informational" modes of descriptions, he explained that either mode is "a confluence of metaphors and methods," a mixture of terms, concepts, and methodologies from both approaches (and others). The "new cognitive science" (Norman, 1981a, 1981b), which has taken shape in the last dozen years or so (Mandler, 1977), appears to have drawn from most approaches, including even early functionalism, that view cognition as an intelligent interface of an organism with its environment. To react intelligently, an organism does not just receive a stimulus, it receives and processes information. As Estes (1975) pointed out, even conditioning "bears on the processes and mechanisms by which animals gain information about their environments" (p. 21). Thus, "we not only should but must be multidisciplinary" in our study of cognition (Estes, 1975, p. 21).

Our present shortcomings in the multidisciplinary approach (see later discussion of long-term processes) highlight the need to view IP in a broad sense. IP is no longer the province solely of "cognitionists" circa 1960-1970. From whatever background and specialization, research is converging on how organisms receive, process, and respond to information from the environment. As a conception, IP thus encompasses sensation, perception, mediation, and response production. Any factor that affects one or more of these processes is of concern, so research tactics range from examinations of physiological and neural functions to studies of sociological and ecological influences. While sociological and ecological influences have been largely ignored in current cognitive theories, there is a movement to pick up where Köhler (The Place of Value in a World of Facts, 1938) and Lewin (A Dynamic Theory of Personality, 1935) left off. More on this later.

As a means of structuring later discussions of cognition and cognitive skills, it would be well to identify the stages and levels of IP as customarily defined. Adapted from Estes (1978b, p. 11), Lachman, Lachman, and Butterfield (1979, ch. 4), and Simon (1978, p. 273), these stages and levels are (1) the registration of stimulus inputs in immediate sensory memory; (2) the coding of features of the stimulus inputs in short-term memory (STM); (3) the relating of contents of STM to contents of long-term memory (LTM) by comparisons with hierarchical networks of feature ensembles comprising the latter. Retrieval of information from STM or LTM involves a search process, usually viewed as serial in nature, at least until recently. Processing during the interplay of STM and LTM includes sequential comparisons of new inputs to LTM contents, with decisions depending on the matches or mismatches that are found. The matches and mismatches are, of course, determined by the purpose of the individual at the time. (4) After processing, a response is produced which will terminate the action if purposes have been achieved, or if

not, the response can be to seek new input or reprocess the old using a different scheme or strategy. The response, of course, derives from past experience as represented in LTM. The contents of STM may or may not be assimilated into LTM at the end, depending, it was once believed, on how much it is rehearsed while in STM.

As stated, IP will be considered in a broad sense of the term; but this customary characterization is a good place to start an analysis of what IP involves because most recent research addressed this characterization. Furthermore, the central concept is memory; it is involved in every phase from the registration of inputs in immediate sensory memory to generating a response from LTM. This conception of memory differs radically from that in psychology prior to 1960. Memory is no longer sheer retention; it is also an agent that acts on and through sensory inputs. LTM, for example, not only contains (coded) static information, but rules for actions as well, including how to subject inputs and other contents of STM and LTM to transformations as they are needed (to adapt to different strategies in problem solving, for example).

Current views of memory often follow closely the storage processes in computers and how stored information, including programs, operates on itself and on new inputs. In fact, many writers (e.g., Anderson & Bower, 1973, 1980; Bower, 1967; Lachman et al., 1979; Newell & Simon, 1972; Rumelhart & Norman, 1975b) developed conceptions of memory through deliberate analogies to computer operations, in some cases considering successful computer simulation of IP as conceived in humans a direct test of the validity of their theories. Others, though recognizing the heuristic value of the computer analogy, point to the dangers involved. Some of the dangers and those who have pointed them out will be identified in later discussions as they apply to particular issues. Nevertheless, critical comments made later in this report notwithstanding, the computer analogy at least has provided models of memory that can account to some extent for the pervasive role of past experience in behavior. We have known for years, for example, that experience affects perception. We have observed that learning, motivation, and stimulus contexts influence what is perceived and how. But only recently have mechanisms, computer-like in nature, been conceived that describe how these influences are brought to bear, specifically through memory actions. The computer analogy has also fostered the development of mathematical models of IP that have contributed much to the analysis of separate processes and to the testing of conjectures regarding them.

## MODELS OF MEMORY

Depending on the theorist, memory includes more, or fewer, stages and levels than were just identified as the core of IP. The variety of models presented in Models of Human Memory (Norman, 1970), for example, illustrates the basis for Postman's (1975) complaint, "the ratio of models to experiments is quite high, although happily still less than unity" (p. 294). In accounting one way or another for almost every breakdown of memory and its functions, Bower (1975) diagrammed relations among a score of components. The discussions that follow provide perspective for memory models, and thereby the later analysis of cognitive skills, first through examples of general conceptions of memories, and then an examination of "dual-process" theory.

CONCEPTIONS OF MEMORY. After describing his transition from a traditional, 1950 conception of memory as mechanical associationism to a "contextual" view of memory, Jenkins (1974) emphasized that "we should shun any notion that memory consists of a specific system that operates with one set of rules on one kind of unit" (p. 793). As he described it, associationism assumes there are fundamental units, linguistic in nature, and relations among them from which all memory is constructed. On the other hand, contextualism assumes events are primary and that the qualities of events determine what is remembered and how. The success of association-based formulas in predicting memory, so Jenkins argued, had been due primarily to their derivation and use in restricted contexts. The formulas could not be expected to generalize across contexts.

A position such as this, which seems to have been well grounded by 1974, the time of his paper, raises several questions, but one is of particular concern: Are there perhaps more than one kind of memory, each with its own set of rules, and does the interplay of the different kinds vary with contexts? If so, identification of the separate kinds, their rules and interrelations, should permit construction of schemes that would generalize across contexts. Several such models had been constructed by 1970 (cf., Norman, 1970) and the number has since increased. As Claxton (1980b) stated, "We find [the cognitive system] constantly analyzed into all sorts of subsystems, ranging from 'Pattern Recognition System' and 'Response Executive' to a bewildering variety of memories: Precategorical Acoustic Storage, Sensory Register, Iconic Memory, Primary Memory, Working Memory, Semantic Memory, Episodic Memory, Response Buffer, and a host of others" (p. 14). Especially influential models, at least in the research they generated, were presented by Anderson and Bower (1973) and Atkinson and Shiffrin (1968).

The Anderson and Bower model was essentially process-oriented. External information, registered by sensory receptors, is analyzed ("parsed") to produce meanings that can be transmitted to a "working memory" within LTM. An "executive" system governs the parsing and the transmission of parsed information to LTM, which in turn outputs to the executive which also controls resulting responses. Atkinson and Shiffrin's (1968) account of these processes tended more to structural concepts: Memory has three "registers," one for sensory processes, one for STM, and one for LTM. Also, STM exercises the executive function.

Both models have been revised by their originators. Anderson and Bower, still focusing primarily on processes, recognized that the original model said little regarding how remembered events are utilized in thought so they expanded the system to address thought as well as additional basic processes such as recognition (Anderson, 1976; Andersen & Bower, 1980). Atkinson, though remaining close to the Atkinson-Shiffrin (1968) model, later pointed out that the separate "registers" need not be considered separate neurological structures; they may be only different phases of activation of a single memory system (Peterson, 1977). Shiffrin (1977) combined the sensory and STM registers because it had been found that immediate sensory contents ("icons") persisted in memory in recoded form. Furthermore, because studies of attention indicated that information from sensory receptors can activate LTM directly without going through STM, Shiffrin reinterpreted the STM-LTM dichotomy: STM is a temporarily activated portion of LTM (Peterson, 1977).

Nevertheless, there are still those (e.g., Glanzer, 1972, 1977) who maintain there are fundamental differences between STM and LTM that imply more than temporally defined processes. That is, the differences imply separate functional structures for STM and LTM (see below).

Baddeley and Hitch (1974, 1977) proposed a working memory (WM) to replace STM in the STM-LTM dichotomy. WM is comprised of several subsystems not unlike those usually considered characteristic of STM. There is a difference, however, in that WM is conceived, as it was in the Anderson-Bower (1973, 1980) model, more in terms of functional than of structural properties. Functions, being dependent on task contexts, are less rigidly (but perhaps more vaguely) defined than structures. In this sense, WM is closer to the layman's concept of what one may "have in mind" at a given moment than is STM. The typical flow diagram in which information from the senses must pass through STM to reach and activate LTM becomes meaningless (Hitch, 1980). A "central executive," a role served by STM in Atkinson and Shiffrin's (1971) system, is separate in the Baddeley-Hitch model. It also has direct access to LTM and can thus activate LTM without "going through" WM.

Although Baddeley and Hitch (1974) said their system was "in the spirit" of models such as that of Atkinson and Shiffrin (1968, 1971), the former also reflects an essentially functional concept of structure as defined by Mandler (1962): "Structures are temporal and probabilistic linkages of inputs and behavior which are available in functional units" (p. 415; all italicized in the original). Accordingly, WM is defined not by an enduring structure, or even characteristics of its contents, but by its mechanisms involved in perceptual and linguistic coding and organization, transfer of information to LTM, etc.

Mandler (1967) expanded on the nature of the linkages that provide functional units. In this model, clusters of elements (words, names of objects or animals, etc.) form hierarchical relations with each other in "permanent vocabulary storage" (he circumvented the STM-LTM issue). His central hypothesis, which has quite a bit of confirmation (Mandler, 1967, 1977), was that encoding of inputs, and their recall, tend to follow the hierarchical clustering in permanent vocabulary storage. Furthermore, separate clusters and their supraordinate-subordinate relations with each other develop with experience.

Mandler's model, as do most memory models, addressed primarily data from standard experiments in verbal learning. It is of particular interest here nevertheless, and for two reasons. First, the conception that immediate recall of inputs has the functional structure of hierarchical clusters in LTM (not Mandler's term), and the evidence supporting this hypothesis, may provide an empirical "handle" on the patently circular concept of "chunking" (see Dual-Process Theory below). Second, the conception can also help clarify the nature of learning hierarchies in theories such as that of Gagné (1962, 1965, 1968). The systems are not completely compatible; but dynamic characteristics that might be ascribed to Mandler's hierarchical clusters in LTM are similar to the roles of learning sets as conceived by Gagne. The similarity opens up at least the possibility that an empirical handle can also be available for assessing the nature of long-term strategies and habits, now called "learning styles," individual learners bring to a training situation. If so, something more than pencil-and-paper tests and job samples can be used to assess the beginning characteristics of students and to individualize their instruction.

Instead of relying solely on status measures, some insight can be gained into the dynamics of how they learn various skills.

Dynamic properties of memory processes are central to the system of Norman and Rumelhart (Norman & Rumelhart, 1970; Rumelhart & Norman, 1975a, 1975b). Extending a point from Bower (1967), vector notations identify the content and direction of processes in a dynamic memory network. The network is characterized by schemata (Norman & Rumelhart, 1975) which are simultaneously discriminative and generalization systems. The schemata underlie analogical thinking and are thus systems of transfer. (The significance of this point for instruction is treated briefly by Norman, Gentner, and Stevens [1976], and at length by Rumelhart and Norman [1981].)

One more type of conception can be added to the foregoing illustrations of cognitive models, one that has particular value for instruction. The focus is on "metacognition" and "metamemory," which are new terms for some fairly old ideas (see Flavell & Wellman, 1977, for earlier thinking on metamemory and review of related research). For example, metacognition, which includes metamemory, encompasses what one is to profit from in acquiring study skills; but modern analyses of the concept go far beyond the puerile guides found in "how to study" manuals. Metacognition incorporates essentially all the processes ascribed to the executive role in modern models of cognition: recognition of the problems at hand in terms of one's purposes; analysis of salient features; "awareness" of the repertoire of available analogical schemata and their domains; planning strategies and scheduling and implementing them; monitoring, evaluating, and regulating actions; etc. (Brown, 1978).

Formalization of the conception as "metamemory" has focused some research on processing variables that have been mostly ignored in formal models of memory (but not necessarily in models of problem solving and understanding). Models of memory have stressed characteristics and processes of STM, WM, LTM, etc., not the "executive" or "central processor." In doing so, they have missed the distinction, critical to real-world performance, between knowing "what" and knowing "how." In an experiment on verbal recall, a subject need know only what. Knowing how is requisite to problem solving, not how as mechanized procedures per se, but how as schemata for selecting and adapting procedures, for acquiring needed information (Brown, 1978). Many problems faced by maintenance technicians could be readily resolved if they could recognize what they do not know that they need to know and where and how to obtain the information. Even leading models of problem solving (e.g., Newell & Simon, 1972) are no help to one who must design an instructional program for maintenance personnel. The models assume that the problem solver has the requisite information formulated in appropriate form, such as could be entered as data and programs in a computer. What is needed is a computer program that can solve the pendulum problem.[1] The computer must be surprised at the problem

[1] In the pendulum problem, the subject's task is to tie together the ends of two strings that are suspended from the ceiling, but too far apart for both to be reached at the same time. The only solution is to tie an object such as a pair of pliers to the end of one, swing it, and grasp it on the return while holding the end of the other string. How must a computer classify a pair of pliers? It would have to see it as a mass, not a tool for grasping, and then intuitively relate pliers-as-mass to gravitational forces acting on a pendulum. See Duncan (1959) for a review of traditional research on problems of this sort.

requirements in view of what is given, and respond creatively to arrive at the solution.[1] Creativity is implied because simply having the necessary information is not sufficient (cf. Duncan, 1959, p. 406).

Existing computer models are notoriously noncreative in this sense (Bower, 1978). They are not limited so in principle, but because of the complexities of programming involved, computer models in the immediate future are not likely to help train a person who must suddenly adapt to unexpected, novel emergencies or to unanticipated problems with equipment. What N. R. F. Maier,[2] for example, studied over the years seems much more pertinent for identifying what trainees need to learn to do and how to teach them.

This discussion has no more than scratched the surface of conceptions of memory, both in terms of the number of models that have been proposed and in the depth of those discussed. It will be sufficient for present purposes, however, if it provides a suitable context for discussing dual-process theory, and together with that discussion, a context for examining processes of cognition that can be expected to have instructional significance.

DUAL-PROCESS THEORY. In his review of research on verbal learning and memory, Postman (1975) titled one major section "The Short and Happy Reign of Dual-Process Theory." He was referring specifically to the STM-LTM dichotomy when viewed either as two distinct processes or structures. However, as was the case once with Mark Twain, announcement of the demise was perhaps premature. Later analyses of cognitive skills take a definite stand regarding this dichotomy. The following discussion gives a basis for the stand.

What is the evidence for two distinct processes? The most often cited evidence is that which led to Miller's (1956) "seven plus or minus two" paper. Miller's point was that the immediate assimilation of sensory inputs, visual or verbal, is restricted to only a few elements (i.e., seven plus or minus two). Such limits, frequently no more than five or even fewer elements (cf. Glanzer, 1972; Mandler, 1967), characterize immediate free recall after a single exposure to, say, a list of unrelated words or digits. Some consider these limits inviolable. In the Atkinson-Shiffrin model, once all slots have been filled, an additional input can be accommodated only if it bumps out one of the present elements (Bower, 1975). LTM has no such limitations; it is essentially unlimited. Hence, the reasoning sometimes goes, there must be immediate, short-term memory processes that are distinct from those of LTM.

Obviously, immediate memory often encompasses many more than five or even nine elements. "Chunking" is inferred to account for the increase. That is, elements become organized into chunks according to, for example, their interrelations. While one may have immediate recall for only seven or so unrelated words, a sentence of many more words may be recalled easily. The

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[1] Requirements here are for flexibility in sets with which problems are approached, and in overcoming "functional fixedness" (restrictive sets). See Greeno, Magone, and Chaiklin (1979).

[2] For a sampling of the scope and depth of Maier's work, see Maier, 1930, 1931, 1945, 1960; Maier & Burke, 1966, 1967.

limits for immediate assimilation then apply to the number of separate chunks, not separate elements. Total immediate memory (STM) is thus determined by the size of the chunks that are immediately formed. Bower (1975) forthrightly points out the circularity of chunking so conceived. (As mentioned earlier, evidence for Mandler's [1967] hypothesis regarding similar clustering in STM and LTM may provide an empirical handle for chunks, removing the circularity.)

It is difficult to see how anyone could consider memory span per se grounds for insisting on a dichotomy between STM and LTM processes or structures. An important training issue is raised later in this regard. However, for the present, an example involving memory for digits will suffice. It is well known that when presented the problem on an intelligence test, subjects of normal intelligence can recall only seven or so digits when pronounced, without emphasis, one second apart. Individual intelligence tests from Terman's to Wechsler's have incorporated such items. Yet, Chase and Ericsson's (1981) subjects, originally able to recall only seven digits so presented, after two years of practice could recall more than eighty. Nevertheless, there appeared to be more evidence for two processes than that provided by memory spans. For example, it seemed at one time that STM coding involved only phonemic processes with no semantic coding. That is, encoding of sensory inputs in STM was achieved solely through symbolic, linguistic "tabs" that served only to index the material in STM. On the other hand, LTM depended predominantly if not exclusively on semantic processes through which relations, organizations, and reorganizations of LTM contents acquired linguistic structure. Later, on the basis of their and others' work, Craik and Lockhart (1972) held that information in STM was probably in visual and possibly in semantic formats as well as phonemic. (Recall earlier mention of Shiffrin's [1977] subsuming the sensory register under STM because of recoding.) Shulman (1971) went even further. After reviewing a large number of studies, he concluded that semantic encoding in STM had been clearly demonstrated; the trouble in finding it had been that it did not occur unless the experimental memory task required it. There is also considerable evidence that some contents of LTM are images, that they are not entirely semantic. In fact, forty years ago introductory psychology texts stressed that children remembered in images because they had not yet developed verbal facility. A later discussion of imagery will return to this issue.

This takes care of only two presumed differences between STM and LTM, however. Wickelgren (1973), while concluding from his review that most evidence allegedly supporting a STM-LTM dichotomy was equally consistent with a single-system model, believed that three phenomena supported only the dual-process model: (1) retention functions have different forms for STM and LTM; (2) STM is affected by interference from "gross" similarity effects, but not subtle or "fine-grained" similarities as is LTM; and (3) some findings with brain damaged subjects such as specificity of memory deficits are easier to interpret within dual-process theory. However, Wickelgren later (1980) equated STM to "active memory," and the latter to attention span. Active memory is an activated subset of "passive" memory, i.e., LTM, from which various memory traces can be in different degrees of activation.

Other possible differences between STM and LTM have been reported. Though he took issue with the supposed implications, Postman (1975) listed encoding variations related to how long material must be retained prior to a test of

retention; effects of modality of presentation on performance; and interactions of serial position of verbal materials to be learned with various experimental conditions. Glanzer (1977) cited others' findings which he (but not necessarily the original investigators) held to support dual memory processes: differences in imageability of words (Richardson, 1974); effects of spacing practice and rehearsal on recall (Pollatsek & Bettencourt, 1976); the effect of articulatory suppression on free recall (Richardson & Baddeley, 1975); changes with practice in primacy and recency effects on free recall (Goodwin, 1976); and the effects of prior recall upon subsequent recall (Gardiner & Klee, 1976). Glanzer did not explain how the findings of these studies support the STM-LTM dichotomy, and in some cases the supposed support is clearly questionable.

Various writers have rebutted each of these points with arguments ranging from counter-examples to rejection of certain findings as being irrelevant. We need not pursue the specific issues; when needed, they will be clarified as functional characteristics ascribed to STM and LTM are discussed. There is one alternative explanation for ostensible unique STM characteristics that should be mentioned, however. It has significance for training and the writer has found no prior systematic treatment of the point. The point is explained in what follows.

Many if not all properties alleged to be unique to STM have been observed in the past to be manipulatable through sets that necessarily depend on LTM. Sets explain why STM can be accessed so quickly. The relation of sets to chunking is apparent in many mnemonic devices, especially those in popularized accounts of "how to improve your memory." Sets play various roles in sensory and perceptual processing, an STM function (Haber, 1966). More subtle, and much more complicated, is the relation of sets to interference and facilitative phenomena. Interference phenomena especially are thought by several writers to be different, in some cases nonexistent, in STM.

Under at least some common conditions, interference can be readily manipulated through task sets. For example, Jenkins and Postman (1949) found that similarity-dissimilarity of sets in original learning (OL) and interpolated activity (IA) had effects on recall of the original learning comparable to those of similar and dissimilar materials to be learned. That is, if OL and IA involved similar sets, retroactive inhibition occurred just as it does for similar OL and IA stimuli; if IA involved a different set, however, retroactive inhibition was considerably reduced (or did not occur at all) just as would be expected with dissimilar OL and IA tasks. Furthermore, Jenkins and Postman (1949) reported that when a change in sets was induced <u>during OL</u> there was an adverse effect on retention.

Sets in the Jenkins-Postman study were induced through performance of the tasks themselves. Earlier, Postman and Jenkins (1948) reported effects on retention when sets were induced by verbal instructions. In this case, instructions on how to proceed with the learning task and retention test had to be <u>comparable</u> to avoid interference.

These results, which are quite consistent with those of similar studies (e.g, Nagge, 1935; Postman & Postman, 1948; Underwood, 1957), illustrate the complexity of the relation of sets to interference, which is usually observed

with no thought of how experimental procedures induce interfering sets even as the experiment progresses (Underwood, 1972). As just mentioned, a change in sets during learning can introduce interference (Jenkins & Postman, 1949). In typical short-term retention studies, sets induced by the experimental procedures or by the subjects themselves may well account for peculiarities of STM interference processes. If so, there are obvious training implications, and it would certainly be worth the time to expend part of our efforts in exploring the effects of sets on STM-like phenomena systematically. It was widely believed, at least until the last couple of years, that information in STM had severe time limits unless constantly rehearsed, that when used the information had to be processed serially, etc. (see later discussion of STM processes). It would take us too far afield in this paper to show how counter examples can be, and have been, generated through manipulations of sets. But again, a thorough exploration of the roles of sets should show how STM-like phenomena can be manipulated to enhance permanent learning and performance. With present conceptions, there is little to do with some STM phenomena except point at them.

Such an effort will require careful logical analyses. As might be expected, phenomena as ubiquitous as sets are not simple. Gibson (1941) discerned some 40 different operational uses of the term in experimental psychology. As Humphrey (1951/1963) pointed out, the number would be increased if the different uses of Einstellung in work by the Würzburg group in Germany were included; and the number would be even larger if the causal attributes of sets in modern models of cognitive and motor performance were added.

On the other hand, the conception of hierarchical learning sets provides a powerful analytic tool for ordering the many manifestations of transitory sets, for that is what learning sets are all about.

Before leaving dual-process theory, a common criticism of the theory should be mentioned. The criticism, which appears in a variety of forms, is that the STM-LTM dichotomy leads to an unnecessary reification of memory structures, and is thus an undesirable violation of the law of parsimony. One of Glanzer's (1977) responses to his critics illustrates the point. Commenting that general objections derive from a preference for a single-process theory, he stated, "when explicit theories have been presented as general single-store theories, they have always turned out to have two elements: two rehearsal processes, two decay processes. Their difference from multiple-store theories becomes difficult to determine" (p. 121). In other words, two rehearsal-decay processes imply two agents (stores) to govern them.

Objections to reification of causal agents are based on more than an arbitrary preference regarding formulations of scientific statements. There is a danger of posing meaningless questions for research--what Planck (1949) called phantom problems--resulting in misguided efforts and useless results. Once the ether was reified, physicists sought its mechanical properties. We research a topic the way we talk about it (Spears, 1960). As Postman (1975) stated, "Once STS [i.e., STM as a "store"] was proposed, its capacity, the characteristics of the units held in it and displaced from it, and its temporal parameters had to be specified" (p. 308). Only a brief review of research in this area reveals a considerable effort to do just that, to determine the form

of a hypothetical entity.[1] As a result, "cognitive psychology has been surprisingly little concerned with learning that changes process and capacity, focussing instead on the demonstration of processes and structures that are supposed to remain unaltered by the experiment, or on learning in the sense of acquiring new knowledge that changes content (you 'know' more) but not process (you cannot 'do' more)" (Claxton, 1980b, p. 9; emphasis in the original). As will be apparent later, "knowing" implies "doing" in much of cognitive theory, but there is still something missing. For the ramifications of the restricted research focus, including social implications, see various articles in Claxton (1980a) and Norman (1981a), especially those by Claxton (1980b, 1980c), Curran (1980), and Norman (1981b, 1981c). The critical self-appraisal represented in these volumes had predecessors, of course (e.g., Estes, 1975, 1978b), but perhaps the number of articles in these volumes addressing the restrictiveness of cognitive research herald a broader outlook for cognitive science in the near future. It must at least have the outlook implied by the above quotation from Claxton if it is to undergird in a systematic way a theory of instruction as envisioned by Glaser (1982).

## SKILL LEARNING, PROBLEM SOLVING, AND EXECUTIVE PROCESSES

A cognitive skill involves cognitive tasks. In and of themselves, the tasks may or may not involve a problem in the sense this term is used in experimental studies of problem solving. That is, the tasks may be performed more or less routinely, even algorithmically, requiring no particular effort of a mental or creative nature.

Even so, novices usually have not yet learned to perform mechanically, to adapt routine operations automatically to peculiarities of varying situations, or even to recognize that given tasks are called for. To them, learning the tasks, the adaptations, the indications of need, involves efforts not unlike those required when presented with a true problem. Moreover, the task may appear ill-structured in that the trainees do not have component skills and knowledge necessary to solve the "problem." They must learn to formulate goals and purposes for the systems they work with and for themselves in relation to the systems. They must learn to assess the situation in terms of the goals and purposes, and of the contextual factors characterizing particular situations. They must also learn to identify pertinent information immediately available, to determine its adequacy, and to acquire additional information as needed.

To deal with the occasion, trainees must develop a suitable set of action alternatives and learn to choose among them. They must become able to evaluate outcomes of their actions and to discriminate between outcomes that clearly fulfill the purpose and those that do so only partially or not at all. As indications warrant, they must alter or change attacks until purposes are clearly fulfilled. Finally, they should be able to repeat the whole process, but with diminishing effort, when similar occasions arise in the future.

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[1] "Form" here refers to the Aristotelian concept of formal cause. Form is essence, and effective cause is derived therefrom. See Spears and Deese (1973).

That these steps have analogs in problem solving is evident from both traditional and modern studies of the process. The primary difference is that instead of having the necessary resources at the outset, the trainee must acquire them. But this too has an analog in problem solving: problem solvers often have to learn the strategies needed (Greeno, 1978a, 1978b).

The analogy between learning routine tasks and problem solving can be pushed too far. However, it is of no serious consequence if it is exaggerated. And there is much to gain from the analogy. Problem solving has been studied throughout this century, and modern cognitive approaches to the topic have shed light on classical issues. The acquisition of cognitive skills has hardly been studied at all. The analogy between problem solving and learning the tasks involved in cognitive skills thus permits extrapolation of research concerning the former to guide training of the latter. At least, the cognitive factors requisite to and involved in problem solving identify the kinds of knowledge one must have for intelligent performance of skills. How close the analogy can be is evident in the discussions below of five executive processes involved in problem solving and in cognitive behavior generally. They are called "executive" because they are the operations ascribed to an executive or central processor in models of cognition.

RECOGNITION OF A PROBLEM. Task analyses typically stipulate that on a given cue a task is to be initiated and implemented. Accordingly, training focuses on cue recognition, interpretation, and ensuing decisions and actions. In a Thorndikian mode, training involves presenting the cues and providing feedback for decisions and actions, giving guidance as required. A cognitive approach emphasizes the internal processes of cueing, decision-making, and the selection, initiation, and implementation of actions.

Cueing in the sense of the onset of a situation requiring action is the domain of "problem" (i.e., task) recognition, or the realization that the situation requires that something in particular be done. A trainee is to learn to analyze the situation so as to key on its pertinent aspects. In this sense, recognition implies discrimination of facets of situations that vary with contexts and with immediate as well as long-range goals. In other words, trainees need to acquire means for structuring situations according to purposes, and the means should be flexible enough to encompass the variety of situations in which performance must occur (skill robustness).

Standard operating procedures (SOP), maintenance schedules, etc., in the armed services attempt to provide comprehensive structures for task performance whereby occasions for actions and the nature of the actions are specified. Skilled personnel must go beyond formal instructions of this sort, however. For example, they regularly encounter situations--"ill-structured" problems as they are called in research literature--that should be recognized, analyzed, and dealt with in the absence of standard instructions. As Simon and Hayes (1976) put it, a leaking faucet says, "fix me." A drip of oil, inconsistent equipment operations, unlikely readings on a test stand, too frequent breakdowns--a host of everyday incidents comprise cues that never get listed in task analyses; nor can all of them be anticipated and included in training.

The training problem is to develop expectancies for what should happen that not only conform to routine operations but which are sensitive to deviations.

That is, persons responsible for, say, operating a piece of equipment should experience a feeling akin to cognitive dissonance when something out-of-line happens.

This use of "cognitive dissonance" is rather mundane compared to the explanatory power ascribed to the concept by Festinger (1957). It refers to the same phenomena, however: motivational states requiring resolutions of deviations of events from expectations. This is not the place to explore the motivational implications for training, but as explained later, they are not trivial. According to Tuddenham (1966), "disequilibrium," a concept very similar to cognitive dissonance, is the central concept in Piaget's theory of motivation: one's understanding of an occasion is in disequilibrium if adaptation to the occasion is not complete, and behavior pursues equilibrium.

Recognition of a problem (read "of conditions calling for a particular task") should involve a comprehension, a schema, that will be in disequilibrium until issues giving rise to task performance are clearly resolved (see Feather, 1971, for discussion of this point in relation to cognitive structures). For problems such as the leaking faucet, such a schema requires a fairly full understanding not only of routine task requirements, but of the situation and any equipment employed. In the past several years, military training has come to emphasize "need to know" as a criterion for theoretical portions of syllabi. In turn, "need to know" has been viewed largely in terms of cognitive requirements for manual operations and for responding to feedback. Probably not every operator, but at least a closely attending supervisor, should have an understanding of principles of, say, equipment functioning that goes beyond everyday operational requirements.

Given requisite understanding, schemata sensitive to disequilibrium or dissonance require perceptual and other cognitive processing of information that is usually ascribed to STM and LTM functions, for example, recognition of patterns of sensory inputs and of matches or mismatches of coded inputs with patterns in LTM. These and related processes are discussed later. It can be pointed out now, however, that the training issues just raised are a new twist. Theories of cognitive performance stress the recognition of a target pattern or a match as the determiner of action (cf. Juola, 1979). If a pattern or match is not obtained, the subject searches memory, transforms inputs, tries new schemes, etc., until it is. The point here is that patterns not in LTM, or mismatches, can be significant cues themselves, and training should target such cueing.

COMPREHENSION OF THE TASK. Greeno (1977, 1978a, 1978b) has focused on the role of understanding in problem solving and instructional issues related to the role (Greeno, 1976; Anderson, Greeno, Kline, & Neves, 1981). (This is not to say that understanding has been slighted by others; rather, that Greeno has chosen to deal systematically with processes of understanding where many others brought them in ad hoc or sometimes assumed them.) He presented (Greeno, 1977, 1978a) three criteria of understanding or evaluating solutions to problems that apply with minimum adaptation to what is involved in comprehending a task. A brief discussion of the criteria will show the relationship.

Coherence. Does the pattern of cognitive relations among components comprise a compact structure? If the relations are poorly integrated, there is a lack

of understanding of the problem solution. Citing Duncker's (1945) distinction between organic proofs and mechanical proofs in geometry, Greeno pointed out that organic proofs, which depend on higher-order relations among steps, are evidence of more understanding than is shown by a mechanical progress from step to step with attention focused only on the justification of each step in isolation. Comprehension of higher order relations involves not only knowing what steps, but why steps are to be taken.

Similarly, one can say that an organic knowledge of a skill represents a higher level of understanding than does only a mechanical step-by-step knowledge. Organic knowledge implies comprehension of the interrelations of tasks comprising the skill (and of the equipment, etc., employed) while a mechanical knowledge might not go beyond a sequential procedure for performing the separate tasks in series. There is no question which level of understanding is necessary for flexibility in skill performance as just discussed. Yet some military training groups specifically object to going beyond gross mechanical levels.

Cognitive integration of tasks is a concern in the design of part-task trainers. However, unlike some motor skills that require coordination of motor dynamics, cognitive skills can be integrated cognitively. As for low-fidelity devices, the integration of purely cognitive skills such as procedures requiring already thoroughly mastered motor actions can be taught with crude mock-ups so long as the learners have clear pictures of how symbolic actions become overtly manifest in real situations.

Correspondence. Does the cognitive representation of a problem have the same structural properties as the problem? As Greeno (1977) pointed out, this criterion has subtle aspects. For example--and here we switch at once from problem solving to task performance generally--it is one thing for an understanding of a skill to correspond directly to the objective aspects of the constituent tasks and the situation for performance. It is another thing to transform the cognitive representation of the situation so as to reconstruct task patterns that correspond in a different way, thereby obtaining a more effective approach to fulfilling the purpose. (These transformations are the essence of skill robustness.) Creative troubleshooting often calls for transformations in order to adapt testing and confirmation procedures. As with coherence, adaptations require comprehension of the situation as a whole--a causal structure for troubleshooting (de Kleer & Brown, 1981)--so that transformed cognitive representations still focus on the purpose and variables essential to its fulfillment.

Connection with Other Knowledge. Is the cognitive structure representing a problem or task connected to other knowledge in a person's repertoire? As a criterion for understanding in problem solving, "connectedness" may mean only that a subsequent similar problem can be solved more readily after a solution is found to the first one. At a higher level, the original problem solution is related to a general principle that may or may not have been already known. For task performance in general, the first level corresponds to what was termed in Section II "near" or "specific" transfer, while the second level, involving general principles, is the basis for "far" or "nonspecific" transfer. In either case, task comprehension would go beyond situationally bound, stereotyped cognitive representations of performance.

PLANNING PERFORMANCE. To the extent a skill requires more than mechanical repetition of habitual operations, effective, efficient performance requires a plan. (A novice, of course, must plan actions that only later will become habitual.) A schema or plan for performance is needed, one with enough flexibility to adapt to the nonroutine aspects of the occasion. The performer should recognize contingencies beforehand and have criteria for decisions the contingencies entail. Through its own organization, the schema should provide an organization for the tasks to be performed. For creative adaptations of skills as in nonroutine troubleshooting, the schema would have to be capable of analogical application. That is, it would be necessary to transform the cognitive representation of the task, or the schema itself, so as to establish the necessary correspondence between them (see preceding discussion of Correspondence).

An important part of any performance plan is a set of subgoals. These are intermediate objectives that can lead directly to completion of the task, or depending on outcomes when subgoals are achieved, they can be points at which progress is evaluated and decisions are made as to the next step. Reed (1977) explained the facilitative value of subgoals in problem solving; they are just as important in any task performance. Troubleshooting, of course, usually involves a hierarchy of subgoals (tests) whose outcomes are bases for decisions regarding the next task (and subgoal). In a sense, even sequential routine tasks comprise a sequence of subgoals: Task B is to be initiated on the completion of Task A; Task C is then to follow Task B; etc.

From a training standpoint, it is not trivial to call routine tasks comprising a procedural sequence "subgoals." In fact, one major difference between experts and novices is that novices lack processes for establishing and handling subgoals (Jeffries, Turner, Polson, & Atwood, 1981). The problem is to teach trainees to comprehend the task organization and then use task completion and related feedback as discriminative cues for the next task. Learning this sequence of subgoals and how to evaluate their achievement is a critical cognitive requirement. Trainees are to incorporate the subgoals into their plans for practice, and at first the incorporation usually has to be deliberate. As training progresses, sequential cueing of this nature may be taken for granted except when generalization of skill performance to varying circumstances is practiced.

A number of skills, controlling the flight of an aircraft, for example, are regularly performed in varying situations. These skills rarely become so mechanized that deliberate planning of subgoals can be entirely omitted. Desired instrument readings change with maneuvers and flight conditions; checkpoints vary with the terrain navigated; etc. Versatility in planning, based on an understanding of the interrelations of numerous factors, can be an everyday requirement.

INITIATING, MONITORING, AND REGULATING PERFORMANCE. The first of these, initiating performance or response production, is an enigma to anyone who seeks an explanation in terms of mechanisms (see also the discussion of this topic in Section IV). Except for the reflex arc--a neuro-motor conception--traditional associationism circumvented the problem more or less axiomatically: a response occurs in the presence of a stimulus with which it is associated. Unless, of course, it doesn't, in which case we resort to habit

hierarchies and probability statements of the axiom. It is difficult to see that modern cognitive psychology helps much in explaining the mechanisms of response production. In a sense, responses become integral to the matrix of components and processes of cognitive structures. Their selection derives from hierarchical determiners developed during information processing. Once selected, responses just happen. The effective cause is the structure of the cognitive matrix per se. (Recall that in Section II "cue" was defined to include associated responses.) For some insightful analyses of this problem, see Allport (1980a, 1980b) and Harvey and Greer (1980).

Perhaps a desire to identify a mechanism of response production is unrealistic, or even irrelevant. At any rate, the mechanism is likely not a part of cognition as such; rather, it is one of the aspects of brain functioning that Köhler (1969) considered "outside" mental activity."[1] The intuitive cogency of the cognitive matrix as effective cause of responses derives from an emphasis on verbal learning and perceptual processes that are encoded linguistically. If a subject is to recall words, and their representation in LTM is semantic, then verbal recall--the response of interest--is ipso facto a manifestation of the contents of the matrix. Why worry about the larynx and other motor mechanisms of speech production?

This view can go a long way. There is little doubt that memory even of motor skills depends heavily on linguistic processes, especially semantic organization. In performing a procedural skill involving a sequence of separate tasks, for example, operators talk to themselves in some fashion. Verbalizations comprise cueing systems, and the problem of response production is no more (or less!) than it is in a conditioned reflex.

But is a linguistically based causal matrix adequate? It is difficult to see how many if not most aspects of complex motor skills can be brought under a linguistic umbrella. Only after mastering the mechanisms of speech can one ignore muscle control of speech production. The trainee trying to learn a motor skill has much more in common with a young child struggling for breath-larynx control than with a subject in a verbal learning experiment. LTM must provide for retention of component organizations that are not semantically organized. Nonverbal acoustic memory (Nelson & Rothbart, 1972) is one example, and Shepard and Podgorny (1978) reviewed evidence that LTM includes some visual components with clearly cognitive functions. It seems that the assumption should be that LTM necessarily includes a host of perceptual components, especially those corresponding to proprioceptive experiences. If not, there must be more than one system for long-term retention and more than one processing system, one set for verbal coding and one for general experiential coding. There are good reasons for rejecting such an inference (Claxton, 1980c). (As apparent in Section IV, models of motor performance do not clarify this issue. In fact, the inclination of researchers seems to be that

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[1] Köhler went further than this. He apparently would have considered many of the mental phenomena of primary concern in modern cognitive research to be epiphenomena--a disturbing possibility in view of current dependence on introspection for data and analyses. (Bower [1978], Evans [1980], and Nisbett and Wilson [1977], made a related point.) In trying to resolve the impasse, Köhler earlier (1959) called not on introspective, but behavioral methodology.

once performance of a skill becomes habitual, it is no longer of theoretical interest [Allport, 1980b; Kinsbourne, 1981].)

It is also less than obvious that production of actions in many procedural skills depends primarily on linguistic processes. If for no other reason, motor skills are retained longer than procedural skills (Prophet, 1976; Schendel, Shields, & Katz, 1978). The thinking is that motor skills have more intrinsic organization. If their organization and production depended only on linguistic representation, why should they be better organized than procedural skills? Furthermore, retention is enhanced when verbal rehearsal is accompanied by actual movements involved in performance and feedback stimulation from them. Even though verbal rehearsal can be substituted on a one-to-one basis for some manual trials in learning some tasks (Wheaton, Rose, Fingerman, Korotkin, & Holding, 1976), it will not work for all trials nor all tasks. And when it works, the learner must have had sufficient perceptual-motor experience to give a sense of reality to verbal rehearsal. Otherwise, mental rehearsal aids only in remembering the sequence of an action; it does not facilitate response production (Newell, 1981).

One upshot of this discussion is that part-task and low-fidelity training devices cannot be designed strictly on the basis of modern theories of cognition and cognitive learning. They make no provisions for retention and utilization, and hence the production, of nonlinguistic components of actions. Part-task and low-fidelity devices can be successful only if substrata of nonlinguistic experience are taken into account. As just suggested, there is likely to be little profit in viewing linguistic and nonlinguistic aspects of skills as separate systems, which could imply they could be learned separately and then synchronized. This would certainly be convenient for part-task training and for the use of low-fidelity devices; but in all probability linguistic and nonlinguistic aspects are part of the same system, in which case their integrative, mutually supportive roles should be a paramount consideration. Fischer (1980) presented a model that could be helpful in this respect.

The other topics of this subsection, monitoring and regulating performance, are covered in various discussions in Section IV. The central process is the recognition and interpretation of cues with attendant actions. The present treatment of the topics will be limited to providing a perspective for them within the framework of cognition.

Earlier discussions of executive processes stressed the roles of task recognition and comprehension and the planning of performance. The occasion for task performance must be recognized, together with contextual variables that indicate required adaptations; skill schemata, the structures of understanding and performance, should reflect coherent integrations of tasks comprising the skills, correspondent relations to the actual structure of the occasion, and "connectedness" with other knowledge sufficient to transcend peculiarities of individual occasions; plans, i.e., adapted schemata, for performance should include checkpoints or subgoals which in turn become cues to continue or alter the action plan.

In problem solving, the checkpoints are the primary concern for monitoring and regulating progress. They are also critical for task performance generally.

In the latter case, however, less deliberated monitoring and regulation are required.[1] In a sequential procedural task, for example, a wrong button might be pushed, an indicator misread, a part of the task sequence reversed. The operator should be able to catch such inadvertent errors immediately on their initiation. In terms used earlier, the operator should experience dissonnance or disequilibrium between events and expectations.

When speed of performance is not critical, action plans can include checkpoints that signal any errors made enroute. The checkpoints would serve the same purpose as multiplying a quotient by a divisor to see if a division problem had been completed correctly. (Computer models of problem solving omit realistic steps such as this.) Procedural tasks and equipment involved in them can be designed to keep the operator safely alert to deviations in performance. When speed is an issue, however, the experience of dissonance is more likely to depend on sensitivity to task-intrinsic feedback, often of a proprioceptive nature. "Open-loop" skills under "programmatic" control (see Section IV) such as rapidly firing a weapon are often consummated by the time feedback is available.

This is not to say that, as some have thought, feedback is not monitored in skills of this nature. A baseball pitcher usually knows when a wild pitch is on the way before the ball leaves his hand. However, whatever feedback is involved, it does not stop the throw; the feedback is operative only at what Glencross (1977) called a higher executive level.

Training personnel to monitor and thereby regulate performance must take the availability of effective feedback into consideration. Executive control of an ongoing action is possible only when there is time to act on feedback. Therefore, rapid, open-loop skills require a higher degree of mechanization, meaning more practice, than do closed-loop skills in which negative feedback has the role of a servomechanism.[2] Even so, open skills are usually learned in a closed-loop paradigm, i.e., by performing slowly and monitoring each stage, interrupting the action if necessary. The training problem then becomes one of capitalizing on the closed-loop paradigm early in training but without introducing persisting interfering closed-loop habits. As has been demonstrated, typists and musicians cannot perform expertly if they watch their fingers (Adams, 1971).

EVALUATING PERFORMANCE. In problem solving, evaluating performance means simply assessing the extent to which a solution is responsive to and resolves the problem as formulated. By extension, evaluating the performance of any task means assessing the outcome vis-à-vis the purpose. This may not be a

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[1]The same can be said for problem solving. Achieving a subgoal such as a test for a component during troubleshooting is of little use if on the way there was an error in the analysis of equipment functioning that rendered the subgoal invalid. As Bower (1978) pointed out, models of problem solving do not incorporate incidental errors, false starts, etc., characteristic of human performance.

2Adams (1968, 1971, 1977) tends to view all motor skills as closed loops. See Section IV.

simple matter in either case, especially when ill-structured problems and tasks are involved.

Analogy problems as often appear on high-level aptitude tests can demand very careful thinking and analysis. An example using an analogy problem will help illustrate the complexity of cognitive processes involved in evaluating performance (and why the Miller Analogies Test can be frustrating). Given the question stem, Hand is to Glove as Foot is to _____, and the options, (A) Ankle; (B) Shoe; (C) Swim-fin; (D) Galosh; (E) Sock. (This example is not recommended as an item for a test; the intent is to avoid prolonging the discussion through combining all examples into one.) Most would probably agree that (B) is the appropriate answer, although a strong case can be made for (D). It depends on how one defines--recognizes--the problem. Glove is an outer covering for Hand, as Shoe (not Sock) normally is for Foot. But Galosh is an outer covering for Shoe. For most persons the "normal" relation, the one requiring least analysis, would be preferred. Suppose, however, that option (B) had not been offered. The choice now, or so we will suppose, is between (D) and (E). Again, Sock is a normal covering, but now one might be forced to consider redefining the problem. Glove protects Hand from the cold, and Galosh protects Foot from snow and slush. Sock offers no such protection. Is the problem one of normal covering or protection? Suppose next that (B), (D), and (E) all are replaced as options with (for present purposes) irrelevant substitutes, leaving Ankle and Swim-Fin as the options to consider. How might the problem be recognized? A baseball Glove is an extension of Hand that aids Hand in its function of catching a ball. A Swim-fin is an extension of Foot that helps Foot in its function of propelling a swimmer. Ankle it seems is not in the running.

In the final analysis, there are several correct answers, depending on how the problem is recognized. Stated formally, the good analogy solver goes through four steps: (1) forming an hypothesis regarding the Hand-Glove relation, i.e., defining or recognizing the problem in a way that creates an expectation; (2) applying the hypothesis analogically to Foot until a candidate mate is identified; (3) testing the hypothesis by discriminating the precision with which the candidate mate conforms to the Hand-Glove relation as (tentatively) defined; and (4) if a less than perfect "fit" is found, returning to the original problem statement for a new analysis of the relation and a repetition of the process. (A really dirty analogy item is one in which several or all options are near-misses unless the relation is defined in terms of the number of letters the words contain, in which case Ankle might be the correct answer in the example above.)

That these four steps are not unique to solving analogy problems on aptitude tests is evidenced by the extensive amount of study of them in traditional research on problem solving. The steps reveal how the evaluative action, step 3, must be derivative of steps 1 and 2, and how the results of evaluation can either terminate the problem or result in further effort through step 4. Common experiences with automobile repairmen reveal that many professional mechanics never get beyond the first two steps. If the symptom is such and such, replace part X. The "repair" is consummated, the customer pays. But was the replaced item actually at fault? As the military has found, many line-replaced units were in perfect working order when received by a repair

depot. What was lacking was appropriate discrimination on the part of the repairmen as called for in Step 3.

As applied to the evaluation of task performance generally (recall that a novice approaches a task as if it were a problem, sometimes a strange one), the conclusion is that adequacy of any skill performance requires that (1) the purpose or goal be clear and well defined; (2) interrelations of component tasks vis-à-vis the purpose be clear; (3) correspondence of the cognitive representation of the task to the situation be complete; and (4) plans for performance include clear (and appropriate) expectations for the outcome.

This discussion may appear to have belabored the obvious. If so, the impression will be different when the complexity of goals and goal-setting is considered in Section IV, along with the effects of fatigue on all the cognitive executive functions just listed. Further evidence of the need to spell out the requisites for evaluating one's own performance was alluded to earlier. Many military training programs focus almost exclusively on manual operations; understanding of performance is restricted to what an operator "needs to know" for mechanical execution of tasks. What was termed "organic" knowledge--the basis for precise self-evaluation of performance as well as for transfer and other adaptive employment of skills--is often deliberately excluded from training.[1]

As stated earlier, probably not every operator needs the scope and depth of understanding implied by the foregoing discussions. Nevertheless, when operators are trained with part-task and low-fidelity devices, eventual skill integration and transfer of the training to operational equipment and situations will require some level of "organic" knowledge. It is just as well to outline what is involved so when some aspects of understanding are omitted from training, one can know what to expect.

SHORT-TERM PROCESSES

"Short-term processes" refer to the immediate perceptual-cognitive interface of a person with a situation to which he is reacting in some manner. They are brief, transitory, and situation-specific. These processes are commonly ascribed to STM, WM, and/or other facets of immediate memory (iconic memory, episodic memory, etc.) working in conjunction with STM and WM. There are four sets of short-term processes of present concern. One, the accessing of LTM and related executive functions, was covered by implication in the preceding discussion of executive processes. The other three are (1) encoding of inputs from the environment, (2) retention/retrieval of inputs, and (3) transfer of the new information to LTM.

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[1]The writer prefers not to document this and a similar earlier assertion with examples because there is nothing to be gained for present purposes by calling the personnel involved to task. Suffice it to say that graduates of one training program to which he raised strong formal objections later had 85-93 percent failures on field tests of some skills. The training targeted STM only, and through immediate repetition of demonstrated steps. There was strong resistance to distributing practice, even to testing the trainees so much as a day following training.

The last three processes could be viewed, as they often were in the past, as more or less independent of each other. Immediate encoding, for example, might index a sensory icon phonemically for storage in STM; as long as the capacity of STM had not been exceeded, all inputs could be retained provided they were constantly rehearsed, and retrieved (recalled) through a serial search of STM for the phonemic "tab"; transfer to LTM depends on rehearsal in STM (to avoid forgetting) until it is organized semantically for storage in LTM.

However, as stated earlier, encoding in STM quite clearly seems to involve the same processing (e.g., semantic organization) that results in transfer of STM contents to LTM. In turn, such encoding processes are rehearsals, at least up to a point. In a training situation, then, encoding is the critical short-term process. Accordingly, the analysis below emphasizes encoding as the central concept. Because of the manner in which encoding is addressed, the other two topics, retention/retrieval and transfer to LTM, are discussed under a single head.

ENCODING. Bower (1972) identified presumed steps of encoding that conform to the view of the process adopted here. First, from a complex pattern of inputs, one or more components are selected for attention. Second, the selected input is rewritten or transformed into a suitable format (e.g., a verbal description). Third, there is then a componential description of the transformed nominal input, i.e., complex features and attributes are abstracted and registered. And fourth, the nominal input is elaborated, through language, for example, resulting in an integration of relations that give the input more associative meaning, hence making it more easily remembered, at least under most conditions.

Encoding is thus an organizational process. The issue is the nature and extent or level of the organization (Basden & Higgins, 1972; Craik & Tulving, 1975; Craik & Watkins, 1973). Simple phonemic or iconic indexing, as would occur at step two, may be thought of as the least complex. It is also characteristic of information for which the capacity limits of STM are most severe, and for which constant rehearsal is necessary for retention. Furthermore, contrary to a once common belief, rehearsal of phonemic information by itself does not ensure its transfer to LTM (see review by Postman, 1975, p. 311f). Step three, componential description, and step four, elaboration, become the basis for long-term retention. Typically involved in these processes are transformations and recoding of inputs according to characteristics of contents and of processing within LTM. Again, encoding is the key concept for training, and the level of organization involved is the determiner of long-term retention. (This last statement will be qualified.)

Selection of Components. The selection of components of sensory inputs is governed by attentional processes. In everyday life, a person processes a myriad of external stimuli, most of which are of no consequence to behavior. Just during a brief interruption of a task such as writing, the gaze shifts to several objects on the desk, a chalk board on the wall, a file cabinet, various pieces of furniture, etc., but none of these is effective in determining what is done next. They are clearly perceived, but they are not cues. The percepts are automatically set aside as the gaze shifts from place to place.

Although incidental learning and related perceptual processes are still of occasional interest in cognitive psychology, theories and empirical studies of cognition are concerned not with inputs such as those but with carefully defined inputs that have known cueing value. The emphasis is certainly appropriate, but this is not to say that it should be an exclusive concern. The earlier discussion of cognitive dissonance or schematic disequilibrium--Simon and Hayes' leaking faucet--is a case in point. It is an extreme case, however; Feather (1971) provided a more general treatment of dissonance. In a verbal learning experiment, the subjects' attention is severely confined. In everyday life, actions require attending to ever changing inputs and screening them for relevance. Unlike a computer model of attention, everyday behavior is characterized by sensitivity to adventitious occurrences, i.e., nonlinear in the sense they result in abrupt changes in what is attended and what is done. (This is a limitation of current models only; computers have been able to handle nonlinear processing for some time.)

There is at present no formulation of attention that takes into account the complexities of the processes involved. Instead, there are computer-like models that stress the rigid functioning of an executive process that is severely limited in capacity. In effect, it boils down to the position that if two tasks are performed at the same time, at least one must be "habitual," thereby requiring no attention (see also treatments of this point in Section IV). Allport (1980b) made a strong case that various attentional phenomena ascribed to capacity limitations actually require diverse explanations. Attention is a complex phenomenon, or rather set of phenomena. Intuitively, we attempt to adapt skill training to the complexity. The question is whether there can be systematic guides for the intuition.

If separated from the notion of a limited capacity executive, the distinction between habitualized and deliberate attending can be helpful. Although issue will be taken with their dichotomy as such, Schneider and Shiffrin's analyses (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977) of attentional factors in automatic versus controlled processing reveals some training implications. According to them, automatic processing follows well established sequences controlled by LTM. Once activated, the sequence is self-determined. There is no stress on the capacity of the system because little if any attention is needed. Controlled processing requires deliberate attention because it involves a controlled search and conscious detection of signals. (Note that Schneider and Shiffrin made no major distinctions among processes of attention, search, and detection, a view adopted here. "In fact, in many cases it is purely arbitrary whether a given study is referred to as an 'attention,' 'search,' or 'detection' study" [Shiffrin & Schneider, 1977, p. 145].)

Generalizing from their data and theoretical analyses, it appears that automatic processing--a must for many skills--develops through practice of controlled processing; that the shift to automatic processing involves a qualitative change in the nature of processing; that the qualitative change is from "varied mapping" to "consistent mapping" (see immediately below); that the learning of controlled processing, and the shift to automatic processing, are facilitated to the extent that sensory inputs can be categorized; and that once stabilized, automatic processing is resistant to change.

As abstract statements, all of these generalizations can be readily inferred from traditional studies of skill learning, if indeed not from studies of conditioning. But we are now more prepared to interpret the conclusions in terms of some specific variables. In Section IV, for example, the resistance to change of automatic processing of motor behavior is viewed in terms of reaction times and motion harmonics. The mapping concept further aids analysis of what is involved. It also highlights an issue in training for skill generalization.

Going somewhat beyond Schneider and Shiffrin's operational use of the terms, consistent mapping involves stimuli, or with practice, categories of stimuli, that individually are consistently either targets or nontargets for selection of inputs. Once learned, the process is simply one of immediate recognition or pattern matching. If the pattern matches, a consistent response occurs; if not, no response, at least not to the characteristics of that input. Varied mapping involves stimuli that on successive occurrences individually change from targets to nontargets and vice versa. Pattern matching must thus incorporate situational variables, sometimes ranging the entire gamut of executive processes discussed above together with the contextual factors they consider. For this reason, deliberate attention on the part of the performer is required, with the correlated reduction in capacity to process information for different purposes simultaneously (Posner & Boies, 1971).

It is apparent that progress from controlled to automatic processing should be facilitated if only consistent mapping is required because only one set of discriminations has to be mastered. Otherwise, consistency must be sought in higher-order patterns that for rapid actions at least must be hierarchically organized (see Section IV).

This last inference goes well beyond Schneider and Shiffrin's data, and apparently their theoretical formulation, and it would be well to clarify a point before further addressing training implications. Categorization as they treated it did not involve hierarchical organization. Indeed, such structures would involve a search, an activity characteristic only of controlled processing as they viewed it. But it is here that issue is taken with their dichotomy and the assumption of qualitatively different modes of automatic and controlled processing. Did the qualitative differences they found reflect typical complex performance or the arbitrary dichotomy of their stimulus sets? As is apparent in Section IV, programs and schemata for automated motor actions must incorporate what operationally Schneider and Shiffrin called varied mapping. Otherwise, motor skills could not be adapted even to minor variations in situations. Furthermore, as everyday experience as well as research implies, trainees' progress from novice to expert is characterized by the development of autonomous hierarchical discriminations of varied inputs as related to purposes (Norman, 1981c).

Although the issue of automatic versus controlled processing was not confronted as such, studies of purely cognitive skills lead readily to the inference that variable mapping occurs in essentially automatic processing: the rapid hierarchical encoding of stimulus letters that develops with practice (Rabbitt, Cumming, & Vyas, 1979); the hierarchical organization of chunking by experts (Chase & Simon, 1973); the more rapid accessing of LTM by good readers (Jackson & McClelland, 1979); the experts' "intuitive"

comprehension of a problem and derivative performance requirements which as Simon and Simon (1978) pointed out, teachers have known about for years (intuition would be the basis for the expert's ability to extract readily the relevant components of inputs [Bower, 1978]); the wide-ranging memory "template" of expert chess players (Simon, 1979, though template was not his term--see Section IV); the "indexing" of recognizable patterns which "guide(s) the expert in a fraction of a second to the relevant parts of knowledge store" (Larkin, McDermott, Simon, & Simon, 1980, p. 1336); the self-sustaining employment of rules by the competent performer (Glaser, 1976); and when applied to continuous ongoing performance following mastery, most aspects of understanding as discussed by Greeno (1977, 1978a, 1978b).

This digression indicates the complexity of the learning one must acquire to progress from novice to expert, and the practical futility of viewing performance in terms of a few discrete, mutually exclusive categories of encoding (or of anything else). Progression is in many respects from controlled to automatic processing of inputs (Neves & Anderson, 1981; Shiffrin & Dumais, 1981). But automatic processing is not a discrete jump from a controlling homunculus--the "ghost-in-the-machine" (Allport, 1980b)--to a mechanical habit. Nor is automatic processing a matter of "consistent mapping" of invariant stimuli in Schneider and Shiffrin's (1977; Shiffrin & Schneider, 1977) sense of the term. Rather, progress is toward consistent mapping of varied inputs onto hierarchical schemata. Moreover, controlled processing is required for autonomous action systems to the extent that performance must be planned and regulated according to the peculiarities of immediate purposes and situations. And contrary to Shiffrin and Schneider's (1977) conclusion, the interplay of controlled and automatic processing should not be viewed as basically interference. In skill performance, planning, monitoring, regulating, and evaluating are controlled processings that must support, and be supported by, automatic processings. The issue is one of integration.

The interplay of these modes of processing is the central concern in training, and the source of a significant uncertainty regarding training design. Should early training involve only consistent mapping? It speeds acquisition and performance stabilizes sooner. But there is a danger of forming restrictive sets such as functional fixedness that prevent creative utilization of skills. There is also the problem that skills so learned are subject to devastating interference when performance conditions introduce varied stimuli. So assuming consistently mapable stimuli are used at the outset, at what point should varied mapping be introduced? How much stimulus variability should there be and at what rate of change? Performance will almost surely deteriorate at first. How much deterioration can be tolerated before it becomes counterproductive? How does spacing of practice affect deterioration?

These and a number of similar questions are not easily answered. In fact, there seems to be confusion over what is involved in answering them, a confusion that may at least have been clarified here. Typical studies, involving relatively simple skills and performance only over a limited time span, pose the question operationally (i.e., experimentally) in such ways that ostensibly conflicting results are common. Newell (1981), for example, concluded that "the benefits of variable practice have yet to be unequivocally established" (p. 223; see also discussion of "The Variability and Specificity of Encoding," Postman, 1975, and "Encoding Specificity," Peterson, 1977). Yet, who would

train a shortstop or a tennis player to respond only in a single manner to balls moving only in a consistent stimulus matrix? Or a pilot to always begin a maneuver from a single complex of conditions and execute it in only one way, ignoring purpose, altitude, airspeed, and wind conditions?

Componential Description and Elaboration. To a great extent, the resolution of the training issues, and of the conceptual confusion, seems to lie in Bower's (1972) third and fourth steps of encoding listed earlier. What features are extracted from inputs and how are they elaborated? What is the relation of componential description and elaboration to functional structures (in the sense of Mandler, 1962) of LTM? We speak here of the activation of habitual processing systems (Paul & Paul, 1968)--learning sets--that trainees bring with them, and which must be built upon, altered, or replaced as performance requirements dictate. Features of an input, abstracted according to individual proclivities, are clustered according to one or more functional structures of LTM (Mandler, 1967). They are recoded or transformed following the psychological equivalent of physic's least action principle, or what some wag called the "principle of cosmic laziness." As mentioned earlier, semantic organization had not been found in STM simply because tasks had not required it (Shulman, 1971).

It is beyond the scope of this report to explain what is known, which is not inconsiderable, about componential abstraction and elaboration processes. Suffice it to identify the nature of the processes involved, and then indicate how they can help clarify confusions regarding variable practice. A variety of mnemonics come into play, most of which have been treated as linguistic in nature (cf. Pressley, Levin, & Delaney, 1982; see especially Bellezza, 1981, for hierarchical mnemonic cueing systems of a linguistic nature). But spatial representations can be very effective (Greeno, 1978b). Also, imagery has had a rebirth. Of five classes of mnemonics discussed by Norman (1976), two (visual imaging and spatial location) clearly have perceptual referents; Turvey (1978) built an entire model of visual short-term processing (he also presented a useful review of research on interference in visual processing); Shepard and Podgorny (1978) integrated perceptual processes fairly thoroughly into the overall cognitive matrix; proprioceptive imaging, even to the extent of comprising the structure of expectations for feedback, has been emphasized in motor performance for some time (see Adams, 1968, for a brief review).

Yet, Anderson and Bower (1973), for example, rejected images in favor of "propositional" (linguistically formulated) representation. As stated earlier, imaging in LTM should be assumed, at least for habitual behavior with motor components, probably including speech. At the turn of this century, research still focused on showing that something other than sensory images comprised thought, an assumption born in the British empiricism of the eighteenth and nineteenth centuries. The rise of the Würzburg school and the fall of structuralism resulted from their success. Even so, behaviorism resorted to proprioceptive representations of speech to explain thought (e.g., Watson, 1930, Chapter 10). The evidence for imagery representations, on which Titchener and Watson based their quite different systems, is now ignored. One experiences déjà vu in reverse. While once we sought imageless thought, we now set about proving that something besides words and semantics functions beyond the stage of immediate sensory inputs. As suggested earlier, if this were not the case, a young child could not remember, much less, think.

Manipulation of Encoding for Training. As stated, modern analyses of cognition enable us to view traditional gross generalizations from learning research in terms of particular processes. This is not to say that the processes are well understood. Rather, we at least know some places to look for guidance for training design. While it is beyond the scope of this report to examine the processes themselves in detail, what is involved can be outlined.

The problem can be approached from several angles, but there are two basic considerations regardless. First, the cueing systems, which include responses as explained in Section II, need appropriate hierarchical structures. Second, disruptive interference has to be minimized during both short-term and long-term processing.

Appropriate cueing structures are a matter of adaptive schemata. These vary with the skill and the conditions for its employment. Therefore, the first step is a cognitive analysis of the skill. Following Greeno's (1977) criteria discussed earlier, component tasks should be organized cognitively so as to have coherent, organic relations with each other. The cognitive representation of the tasks should be such that the performer can, and is likely to, transform them and situational inputs to achieve correspondence. Connectedness should be such that specific or nonspecific transfer is made readily.

What is involved in an analysis of this sort goes far beyond task analysis as ordinarily conceived (Caro et al., 1981; Prophet et al., 1981). It is necessary to delineate the contents and functional structures of schemata. For examples of task analyses in cognitive terms see Champagne, Klopfer, and Gunstone, (1982); Greeno (1976, 1978b); Newell and Simon (1972); Resnick (1976); and Simon and Simon (1978). These examples are quite involved, but as Farnham-Diggory (1976) said, a belief that simple representations of cognitive task analyses can suffice is an illusion. A fairly detailed analysis is needed to guide the manipulation of short-term processes during training, and to design instructional equipment to aid in the manipulation.

The manipulation of encoding processes would focus on the kind and level of elaboration required to conform to the long-term cue-response structure defined in the task analyses. There can be a variety of elaborative processes and strategies (Montague, 1972, 1977). Left to themselves trainees are likely to use idiosyncratic strategies that may be less than optimal (recall the psychological equivalent of "cosmic laziness"). Training design can forestall this, however. Appropriately timed questions can force elaborations that otherwise might not occur (Anderson & Biddle, 1975). Imaging and other mnemonics can be encouraged (Atkinson, 1975; Frase, 1975; Montague, 1972); and because visual imaging incorporates spatial relations--Baddeley and Hitch (1977) might say is spatial relations--it can be expected to lend reality to the cognitive rehearsal of movements (Huttenlocher, 1968). (For reviews of mnemonic methods, and questions that need answering, see Bellezza, 1981, and Pressley et al., 1982.)

There are numerous devices for manipulating encoding. It was inferred years ago that spacing of practice can have positive effects on the kind and amount of encoding that occurs, as can delaying feedback (Kulhavy & Anderson, 1972; Sturges, 1969, 1972). Stimulus predifferentiation, which has been treated only superficially in research on military training, has also long been known

to transfer to later learning (Arnoult, 1957). Numerous studies of advance organizers have shown clearly positive effects, but the number of negative results indicates a need to understand them and their roles more fully (Barnes & Clawson, 1975). Just how instructions are given (Hayes & Simon, 1974; Simon & Hayes, 1976) and how task requirements and formats are presented (Hayes & Simon, 1977) make a difference. Cognitive systems employ "utility considerations" that can incorporate a number of mechanisms in different ways, with the efficiency depending on perceived parameters of the task (Navon & Gopher, 1979). And there is still emphasis on guiding learners' elaborations to rules and general principles that was stressed by Haygood and Bourne (1965).

The complications involved in manipulating encoding processes lie in complexities of interference. Until modern analyses of information processing, interference was viewed in terms of its gross effects on criterion responses, i.e., response production. No wonder there was confusion over the effects of spaced versus massed practice and of delays in feedback. As just stated, one has to consider elaborative processes that may or may not occur in the interim. We now know that the gross effects are resultants of what happens prior to response production, of complex interplays of competitive versus facilitative components at every stage and level of processing. In fact, localization of interference has been a major criterion for identifying separate perceptual, cognitive, and motor processes and distinguishing among them. The complexity begins with attention (cf. Mackintosh, 1975), the sensory input stage, and the first perceptual processing of the input (cf. Breitman & Ganz, 1976; Duncan, 1980; Hayes-Roth, 1977; Kaufman & Levy, 1971; Turvey, 1978). Interference at these stages was not considered in earlier learning experiments (it was in studies of sensation and perception per se, however). Interference continues, and in ways not understood, through competitive modes of subsequent encoding, feature abstraction, elaboration, even groupings within hierarchies (Postman, 1975). Interference affects long-term schematic processes, which also generate their own interferences. And the eventual impact on response production depends on how learners resolve the interference.

In addition to clarifying loci of interference, modern analyses of information processing bring to light possible mechanisms of interference that were heretofore ignored. Traditionally, stimulus and response, i.e., input and output, compatibilities have been considered the primary sources of competition that lead to forgetting or disruption of performance. It now seems clear that competition can arise from the processing itself. For example, two concurrent tasks may be performed without difficulty under most conditions, yet at the limit (of speed, for example) seriously interfere with each other. The interference could well be due to both tasks using the same mechanisms of error detection and thus regulation (Allport, 1980b). Under normal conditions, employment of the mechanisms may be alternated or otherwise coordinated; at the limit, the coordination may prove inadequate or even impossible. Could it be that training for tasks that must be performed concurrently under stress should target separate systems for error detection? As for the compatibility issue, i.e., stimulus-response similarity-dissimilarity, it may or may not help to analyze the problem in terms of cognitive similarity (Ortony, 1979; Tversky, 1977; see also Gagné, Baker, & Foster, 1950, and Wallach, 1958, for an earlier recognition of the need). At any rate, it would be closer to the problem than the traditional treatments of similarity and consistency discussed in Section II.

When interference was mentioned earlier as one of two basic considerations in clarifying training issues, disruptive interference was emphasized. The reason was that when viewed at the level of separate cognitive processes, interference may be desirable as well as undesirable. Not only can visual pattern masking obscure a signal, it can eliminate irrelevant stimulus inputs that would confuse a signal. At a higher level, transitory sets may predispose one to misinterpret some information, yet enhance the processing and utilization of other information; or long-term learning sets that are rigid and inflexible will prevent analogical schematic performance, but they are needed for skills requiring stereotypy of actions. Such is the problem of negative versus positive transfer.

Cognitive task analyses delineating these processes should among other things clarify the need to provide for consistent versus varied stimulus mapping, indicating the range and hierarchical order of LTM patterns to be matched to inputs. This knowledge is critical to optimum design and use of part-task trainers, for the hierarchical order of patterns of inputs in part-tasks in relation to whole tasks will determine how part-tasks must eventually conform to an integrated structure. The instructional goal is to bring varied mapping of stimulus inputs to taw. What transformations can be learned for skill robustness, for making varying patterns of inputs have topological discriminative consistency even though task and situational requirements ostensibly vary? It was suggested earlier that hierarchical processing is required, characterized by Greeno's (1977) criteria for understanding, especially transformations required for correspondence.

RETENTION/RETRIEVAL OF INFORMATION AND TRANSFER TO LTM. If encoding does not advance beyond the essentially perceptual process of attentional selection, or perhaps simple phonemic or other indexing, time limits on retention are severe unless there is fairly constant rehearsal. The maximum duration is generally no more than 20-30 seconds (Lachman et al., 1979). Several studies have attempted to determine the reason for the loss. Does retention simply decay with time or is forgetting due to subsequent inputs that "bump" old contents out of a process of severely limited capacity? The answer to this question need not concern us. As explained under Encoding, the "capacity" of STM can be manipulated; as stated earlier, Chase and Ericsson's (1981) subjects could retain more than eighty digits in STM after two years practice. The important point for training is to distinguish between what can, or should, be forgotten and what should not, and adapt training procedures accordingly. In entering data into a keyboard, for example, a unit of four or five digits has to be retained no more than a second or so at most. A skilled operator may well perform such a task perceptually (recall that associated responses are part of the cue matrix). It is actually desirable in such instances that the information be lost from STM immediately after entry. Otherwise, it would likely interfere with the next data unit to be entered, causing errors. Hence, both speed and accuracy depend on as little phonemic indexing as possible. "Touch" typing and similar keyboard operations accomplish just that.

Other kinds of inputs need longer, but still relatively brief, retention. Such would be the case when all pertinent information is not simultaneously available or when decisions or actions indicated by the input endure for several seconds or minutes. An example is a pattern of variable instrument readings on an electronic test stand. In this task the operator needs at

least a rehearsal strategy to ensure adequate retention of moment-to-moment inputs and their changes. If actions or judgments depend on patterning of inputs, encoding must advance at least to the level of feature abstraction (Bower's, 1972, step three). Elaboration may be required as well.

Except for the purely perceptual encoding in the first example, these processes have been considered to lead to long-term retention. While most theorists today no longer believe that simple rehearsal is effective for transfer to LTM, a few theorists have recently held out for at least some transfer (e.g., Glanzer, 1977). But this issue need not concern us either except as explained below. To be functionally effective, contents of LTM require organization, a process that must begin during encoding.

This is one example of the need for cognitive task analyses. What should trainees process rapidly and forget rapidly? What should be rehearsed for temporary maintenance only, and what rehearsal strategies are most effective in minimizing interference? What kinds of patterning of inputs, i.e., cognitive structures of features to be abstracted, are needed for discriminative cueing? What should be elaborated and how? What can be taught with, say, a low-fidelity device without introducing inefficient abstracting and elaborative schemes? Such could happen, for example, if trainees learned habitually to route symbolic inputs through a semantic elaboration, when with actual equipment the stimuli would have physical representation and the input should be processed only at the perceptual level.

Training should target the answers to these questions, and it is apparent that grossly generalized training principles provide little guidance. "Trainees should practice verbal rehearsal"--of what in particular, focusing on what abstracted features, and for how long? But there is an additional question: What information should be transferred to LTM?

This last question reveals a serious gap in our knowledge of memory. Craik (cited in Bower, 1975) made a very useful distinction between maintenance rehearsal and that involved in semantic organization. As just suggested, maintenance rehearsal results in little if any transfer to LTM while semantic organization does. But does all organized knowledge wind up in LTM? Should it? The gap in our understanding is illustrated by a memory peculiarity of waiters who take pride in their profession.[1] Prideful waiters do not write down each diner's order. When after an hour, often much more, time comes to prepare the check, there is no difficulty in remembering what each diner ordered. After the check is paid and the diners leave, but return shortly to question the waiter, he has forgotten almost all of their orders.

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[1]This example is presented as an anecdotal observation. It follows my memory of a study done many years ago. Unfortunately I have not been able to locate the report or a reference to it. According to memory, the study was done by Kurt Lewin and/or one or more of his colleagues to demonstrate the efficacy of Gestalt patterning in what we now call working memory. As remembered, the example was much more impressive than this account, but I fear overdoing it. As presented, the observation can easily be confirmed.

This is apparently an everyday occurrence for everyone, though probably in most cases the occasion of closure[1] (paying the check) is not so discrete, so the forgetting is not abrupt. The point is that considerable elaboration and organization is necessary to retain such information, but it has no place in LTM as conceived. An operator must have appropriate sets to elaborate and organize information derived from instruments and a host of other external sources, and the sets must be maintained from minutes to hours, even days. But the operator who stored the information permanently would find his LTM as hopelessly cluttered as that of a hapless waiter who could never forget anyone's order.

The concept of working memory helps here, but as presently formulated it is hardly a comprehensive conceptual tool. It does not guide a training developer in providing for LTM or not, according to need. There are various empirical data, old and new, regarding intentional learning, differential learning of materials, etc., that are applicable. But though the roles of these factors have been recognized in modern theories of memory (e.g., Montague, 1972), they have not been formulated sufficiently to guide systematic extrapolation to training problems. An operator must intend to learn, from moment to moment or hour to hour, the status of various inputs, to differentiate among them, even if they are to be washed out once the task is complete. What is the difference in intentions or differentiations that lead to long-term retention and those that do not? Vividness is one difference. As Mark Twain said, "A man who sets out to carry a cat home by the tail is in for an experience he will never forget, one that will never grow faint or dim." Yet even in its simpler aspects, vividness is a complex phenomenon and its manipulation quite complicated (Taylor & Thompson, 1982).

As Montague (1972) titled a section, "To Store or Not to Store, That is [the] Selection." The designer of training and related equipment must find his own answers. The guiding hypothesis is that cognitive task analyses should distinguish clearly between content to be retained indefinitely and schematic processes for organizing content. The processes, necessarily analogical, are to operate on temporal content, yet be independent of temporal content except to the extent its transformations are required to establish functional equivalence to LTM content associated with the processing. Training to process thus involves all the varied stimulus mappings and variable training that lead to generalized discriminations.

## LONG-TERM PROCESSES

Long-term processes are essentially those that underlie schematic operations discussed under Executive Processes, and feature abstraction and elaboration discussed under Encoding. They involve both organized content and

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[1] "Closure" is used in its technical sense in Gestalt psychology. A lot of work was done on the effect of lack of closure on retention following Zeigarnik's 1927 report that uncompleted tasks were recalled better than those that had been completed (cited in Woodworth & Schlosberg, 1954). The theoretical issue was poorly defined so it was not clarified. The Zeigarnik effect has been recognized in more recent cognitive psychology, however (Baddeley, 1963).

schemata for manipulating the content according to situational inputs. Except in these contexts, which by no means are minor considerations, long-term processes have received little attention in modern cognitive theories.

So there remains to emphasize three points that are implicit in cognitive science but which have been known for some time. A simple example illustrates the points explicitly. A "memory expert" asks twenty persons in the audience to each call out one word. A twenty-first person is designated to write each word down in numerical order so the expert can be checked. When all words have been called, the expert then repeats them forward and backward. He asks the audience to call numbers from one to twenty and immediately gives the word for each numerical position called.

Very impressive. But anyone with normal intelligence can do it with the right preparation. Indeed, normal people perform much more complex memory feats throughout the day. With due caution to focus on the learning and behavioral issues, not the mnemonic preparation, how the memory expert prepares for the task reveals the most fundamental considerations in complex behavior.

The expert has his own list of twenty words. First, these words are thoroughly mastered, including their numerical designation. If someone slipped up behind him and shouted "thirteen" his thirteenth word would have flashed in his mind by the time he gave a startled jump. Second, each of his words has a broad associative context. That is, it can be associated meaningfully and immediately with any word likely to be called.

So far, the numerals 1 to 20 satisfy the requirements for the expert's list of words. If the fifth word called is Clock and the sixth Table, one can readily come up with 5 Clock(s) and 6 Table(s). But it won't work. Everything is enumerated and all discriminations occur in the enumeration--5 is less than 6--not between Clock which is not less than or anything else than Table. (Let's see now, was it 5 clocks and 6 tables--no, maybe it was 12 Clocks and only 2 Tables.)

The expert's words must have discriminative associations. If the fifth word in his personal list is Hand and the sixth Leg, he is not likely to confuse "Hand on Clock" with "Leg on Table".

These discriminative associations may be short-term or long-term. In teaching what he is now explaining, the writer has used this stunt in two applied learning classes the same term without disruptive interference. Though this statement is important as suggested above, here it pursues the gimmick, not the learning principle, so we will drop it.

The learning, ultimately performance, principle is that trainees should master a broad, discriminative associative[1] structure for their skills.

[1] "Associative" implies no particular theoretical position on the "association" versus "integration" basis for LTM processes (see Claxton, 1980c). Although the writer, along with others (e.g., Anderson & Bower, 1980), leans toward an associative interpretation of most LTM processes, the term is only descriptive as used here. There is no need to fetter the concept with theoretical baggage.

Breadth and discrimination were treated in detail under Executive Processes and Encoding. The need for mastery is intuitively clear if we ask whether the memory expert could succeed in gulling his audience if he had to struggle to recall his own list of words; or just as important, if he could not remember immediately the serial position of each word in his personal list but had to do a serial search, counting through to, say, 18 if a member of the audience said, "What was the eighteenth word?" (The reader can surely infer the writer's opinion of "training to proficiency" when this criterion is defined as it often is in military training.)

Here we confront the search issue in retrieval of information, another of the many processes that were not even considered until modern cognitive theorists forced us to recognize the gaps in our knowledge of what goes on between a stimulus and its response. How does one retrieve information from memory? There are many ways one might retrieve, so what strategies of retrieval should trainees learn? What should they key on? How can retrieval be taught?

It is easy to program a computer to do a serial search, for example, to start at the expert's first word and by seeking matching patterns continue until the numerical tab for a word matches the number of the audience member's challenge. Computers do this quickly, much more quickly than can our expert who should smile urbanely while giving an immediate answer that obviously did not require a lengthy serial search. Yet because of the near equivalence of the computer's and subjects' speed in serial retrieval of words in verbal learning experiments, it has been argued that retrieval is basically a matter of serial searching (e.g., Anderson & Bower, 1973).

Now there is ample experimental evidence that all memory searches are not serial (Anderson & Bower, 1980; Evans, 1980). Seriality may characterize STM if encoding has not progressed beyond the phonemic or indexing stage, but what of LTM and results of STM encoding that depend on contents and processes of LTM? Without prejudice as to the training value of modern conceptions of retrieval, or traditional interpretations of what is involved in recall in verbal learning experiments, the provincial interpretative restrictions of laboratory studies should be recognized. Surely, not even an avid proponent of serial search would insist that all contents of LTM are candidates when a STM pattern is to be matched to a LTM pattern. There must be some selection at the outset. Otherwise the search would require delving into the nether reaches of LTM, including the unconscious--the realm of the Id, what Rex Stout's fictional detective Nero Wolfe likened to a sewer. To check through the indexing tabs, let alone semantic and other patterns, of contents of an operator's total LTM would take the computer on an interminable (but interesting) journey.

This reductio ad absurdum is to emphasize two points. First, until quite recently, theoretical formulations of retrieval processes have been more appropriate for computer models of learning experimental verbal tasks than for explaining retrieval in everyday life. In the models, retrieval, and thus thought, become an action of pure intellect across a highly restricted domain, an action that conforms to the rules of logic. Strangely, Henle (1962) even argued that when a person commits a logical error, he is still thinking logically. The error arises from changes in the material from which reasoning

proceeds. As Estes (1975) insisted, there is more to the brain than cortex. Other parts evolved earlier and are just as important in behavior in modern man as they were to his ancestors (see also Evans, 1980). For motor skills especially, the roles of lower brain systems in LTM should not be ignored. The rhythm and harmonics of coordinated actions emphasized in Section IV are not matters of logic. Earthworms have both rhythm and harmonics.

The second point of the reductio ad absurdum was to emphasize the need to focus on the selective processes of retrieval. Traditionally, successful selection was equated to memory as sheer retention, so interest went no further than identifying factors (sets, vividness, amount of practice, etc.) that affected response production such as verbal recall. Tapping the contributions of cognitive science, a distinction should be made between long-term retention qua retention and response production. Selection, an executive function, is itself an important consideration in training. Response systems in LTM are of no value to operators if they cannot access them as needed, when needed, and without disruptive interference.

As with other topics, the present purpose is to identify components of skills to consider in designing and using training equipment, not to explore their ramifications and details of their utilization. It would be well to mention, however, that there are some formulations of selective processes that reveal what a trainee should learn. Greeno (1978a), for example, discussed means-end analyses, constructive searches, transformations, and other executive processes in a way that identifies particular capabilities trainees should acquire. Greeno related these processes to three basic types of problem solving; but as before, there are clear analogs to problem solving in task performance generally, and especially in the learning of tasks. Evans (1980), for example, considered the means-end analysis in problem solving studied by Newell and Simon (1972) a valuable heuristic for understanding thinking in general.

## MOTIVATION

Modern cognitive psychology is often criticized for neglecting motivation. In one sense this is a valid criticism. In positing purposive behavior at the outset, cognitive processes pursuant to goals have been the emphasis in empirical and theoretical research, not the processes whereby goals are established and become functional. On the other hand, there is more motivation in cognitive psychology than might meet the eye. A brief historical digression will provide a basis for revealing it.

The first point is that motivation should not be equated to desire, want, or even interest. These cognitive-emotional states may, and as often as not do, lead to no productive behavior whatsoever. Spears and Deese (1973) explained how self-concept, to many an all encompassing motivational system, does not go beyond Aristotle's concept of formal cause. Form is essence, and matter strives to acquire form. Ergo, motor, moving, or effective[1] cause is derivative of form; all that is needed is the form--the desire or interest.

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[1]As translated, Aristotle referred to "efficient" rather than "effective" cause. "Effective" is used here because in the context of training, "efficient" does not have the connotation needed.

Any motivational concept such as desire or interest can be substituted for self-concept in Spears and Deese's analysis without changing the meaning or the cogency of their argument. Their point was that without a more or less independent effective cause--the only recognized causal agent in the physical sciences--there is no way to derive behavior. To be a useful concept, motivation has to incorporate directed actions. A desire or interest cannot affect learning and performance unless it is implemented.

Woodworth (1918/1970) distinguished between "drive" and "motive" on this basis. Motivation is direction. In developing principles of human adjustment, Shaffer (1936) joined a growing trend in separating the energy component from the directive one, calling the former "drive" and the latter "motive." This type of distinction became the basis for "habit" in the behaviorism of Hull (1943) and Guthrie (1935). Learned habits, the responses attached to stimuli, are directive forces and hence are motives. As Shaffer explained, anyone who has formed a habit of reading a newspaper will read newspapers. Desire to read no more creates the habit than habit creates the desire. Estes (1958) took a similar position in earlier formulations of a stimulus-sampling theory of motivation.

There are serious weaknesses in the S-R conception of motivation (Bolles, 1975; Kendler & Kendler, 1975), but the shortcomings are not in the concept of direction. Rather, they are the assumed S-R mechanisms, plus undue dependence on the biological concept of homeostasis. Drives were assumed need states arising from physiological imbalances; they were complexes of stimuli (Guthrie, 1935; Hull, 1951), or in the earlier Hull (1943), sources of drive stimuli. But as White (1959) showed clearly, after "its homeostatic chores are done, [an] organism is alive, active, and up to something" (p. 315). In brief, traditional behavioristic theories of motivation could not account for a kitten playing with a spool.

Accordingly, research in developmental psychology turned to cognitive factors as mentioned earlier--an evolutionary based compulsion for competence (White, 1959); cognitive dissonance (Festinger, 1957); discrepant cognitive organization (Feather, 1971); and Piaget's schematic disequilibrium (Tuddenham, 1966). Hunt (1961) held that motivation "inhere(s) in the processing of information itself" (p. 253), which in turn results from means-ends experiences throughout life (Hunt, 1960).

In cognitive science, the directive components of behavior become those factors that govern pattern matching and response selection and production. Therefore, as stated earlier when this topic was discussed, the cognitive matrix itself is the effective cause of responses, and hence of direction, as viewed in modern cognitive psychology. Instead of criticizing cognitive science for neglecting motivation, perhaps we should focus our concern on its failure to come to grips with selection and production.

Allport (1980a) attempted to do so in his response to criticisms regarding the alleged slighting of motivation. The same could be said of Harvey and Greer (1980). A similar point was made earlier by Bolles (1975) and Bower (1975). To appreciate the implications of their argument, one has only to peruse the 1980 Nebraska Symposium on Motivation (Howe & Flowers, 1981).

This is not to say that modern cognitive theory treats motivation adequately. As discussed earlier, one may wish to know the mechanisms of response production, especially for responses not tied directly to linguistic processes. There is also a general ignorance concerning "the affective tinges that colour our awareness of all cognition" (Claxton, 1980, p. 17; emphasis in the original).

But even so, there remains ample substance for a training developer to contend with. An obvious example is the need to tap trainees' habitual action systems that lead to constructive responses whatever they might do. A common observation is that desires and interests often lead to nothing more than talking about a matter. Military routine abets this tendency daily. What is needed is a felt dissonance or disequilibrium on the part of trainees that can be resolved only by constructive action--and being sure trainees have the skills to take the action without undue difficulty and discomfort (see discussion of need for professionalism by Caro et al., 1981). Training devices, especially those of low fidelity, pose a problem in this respect because of negative attitudes that often develop toward them. Attitudes are potent motivational systems, and negative attitudes are accompanied by a host of generalized diversionary, nonconstructive response systems that especially affect the setting of one's performance goals. Negative attitudes can be dealt with, but not superficially (see Caro et al., 1981).

This facet of performance just mentioned, goal setting, is a crucial concern in training. It is treated at some length in Section IV as a cognitive component of motor skills. What is said there is completely applicable to cognitive skills. Discussion is delayed only because an immediate context of goal setting is needed for particular issues in motor performance.

# SECTION IV

# ANALYSIS OF MOTOR SKILLS

The purpose of this section is to extend the analyses in Section III to cover motor skills, and to examine dimensions of motor behavior that are not represented in purely cognitive skills. To avoid undue redundancy, one or both of two general criteria, applied rather loosely, governed selection of motor dimensions to discuss. First, their roles and qualitative and/or quantitative characteristics change with practice. Second, their transfer characteristics merit special attention. As with cognitive skills, the emphasis in the analysis is on skill characteristics emerging from well controlled, i.e., laboratory, research.

The discussions that follow are grouped under five major heads: (1) models of motor skills; (2) motor aspects; (3) perceptual aspects; (4) cognitive aspects; and (5) organization of motor skills. Treatment of situational aspects such as task demands, time constraints, interference, etc., is integrated into the discussions of the last four major topics. The reader will note that the analyses of two of these topics, motor aspects and perceptual aspects, apply as presented only to skills that depend on special coordination of movement. The last two topics are extensions of material in Section III as it applies to all motor skills.

## MODELS OF MOTOR SKILLS

Models of motor skills are not developed as fully as those for memory and cognitive functioning. They lack both the detail and comprehensiveness of cognitive models. One reason is they focus on simple movements in clearly defined tasks, such as involved in moving the arm a defined distance or "aiming" the hand toward a terminal goal. An important exception is tracking experiments in which subjects directly or through manipulation of instruments attempt to maintain contact with a moving target.

Except for problem solving, cognitive models also focus on restricted tasks such as those involved in verbal learning and memory experiments. There is an important difference, however. When dealing with verbal processes, a researcher or theorist is studying a highly generalized discrimination system, one so pervasive in complex behavior that it can be said to represent the entire significance of being born human. Simple movements and tracking performance do not have such generality, at least not ostensibly. In fact, the common belief--one that is criticized later--is that motor skills are specific to particular tasks. They do not generalize except to other tasks that are highly similar in physical characteristics. With a restriction such as this, motor theories seldom pursue generalization of skills, a shortcoming that limits their value in training.

The limitations are apparent in the following discussions of two types of models of motor skills: "channel" models and "process" models.

CHANNEL MODELS. Channel models could be termed "structural" in the sense the term was contrasted with "process" in models of memory discussed in Section

III. "Channel" is used here, however, because that is what these models are called. There are two basic types, single-channel models and multi-channel models. In either case, "channel" denotes a presumed neural network in which all information related to an action is processed.

Single-channel theories assume there are definite restrictions on the amount of information that can be processed at one time because all processing must occur in a single unipurpose network (Kinsbourne, 1981). If two tasks are to be performed concurrently (time-shared), it is necessary to attend each on a serial basis, either by completing one before starting the other or through successive interruptions of each so that attention can be shifted periodically. If a person does two things at once (talking and walking) that require parallel, not serial, processing, at least one of the actions must be so habitual that it requires no attention. If habituation is the case, then the skill is no longer of interest in single-channel theory because it is no longer processed in the channel (Kinsbourne, 1981). Single-channel models thus are restricted to skills that require deliberate attention, skills that have not been mastered sufficiently to be performed automatically. Yet, these models are typically not concerned with skill acquisition. In the majority of experiments addressing these (and other motor) theories, data are not even collected until subjects have practiced enough for performance to stabilize.

From a training standpoint, it is necessary to know how a skill develops from the beginning. Just as important is the nature of skill habituation and how to achieve it. Furthermore, a number of complex skills require attention for their several component tasks--controlling the path of an aircraft while scanning various instruments and communicating with the ground. In single-channel theory, one would have to consider all tasks a single action or else insist that no more than one requires attention. Otherwise, there must be continual intertask interference, not only when first practicing the integration of the tasks as can be expected, but indefinitely. Obviously, the fallacy of affirming the consequent arises when complex skills are at issue. If the performer does more than one deliberate thing at a time, they really comprise only one action by definition of single-channel processes.

Multi-channel theories assume at a minimum that capacity to process information can be allocated either to separate channels or to functional divisions within one channel (Kinsbourne, 1981). They recognize time-sharing not only of actions but of attention. They also seem more consistent with observed patterns of interference among actions, especially patterns arising from same versus different sensory-responding modes (cf. Allport, Antonis, & Reynolds, 1972; Kantowitz & Knight, 1974, 1976; Kinsbourne, 1981; McLeod, 1977, 1978; Posner & Boies, 1971).

As with the single-channel models, however, multi-channel models at present, qua models, do not offer much for training. Their adaptability to training issues is hampered by postulated exclusiveness and rigidity of channel domains. Even the research they have stimulated has been directed more to determining the structures and boundaries of channels in the nervous system than to what performers do and how they learn to do it. As for the rigidity of channel domains, refer to the Section III discussion of multiple versus single LTM systems; for a criticism of the misdirected research, see discussion in Section III of structures such as "stores" as Aristotelian causal forms.

PROCESS MODELS. As pointed out early in Section III, "process" has two meanings in conceptions of behavior. One use of the term is generic as in "information processing." This use includes channel theories. The other use of the term is to designate conceptions that focus on processes per se as opposed to processing structures. It is the latter use, processes versus structures, that applies to process models of motor skills.

Three types of process models are of interest, plus a fourth orientation that has not been systematized sufficiently to be called a model. These are "closed-loop" models, "open-loop" models, and "schema" models. The fourth type of conception views the nervous system as a dynamic network in which processes interact according to the demands of overall adjustments to task requirements, and to specializations of "regions" of the brain.

Closed-loop, often called "cybernetic," models of motor performance developed along with the more general ideas of cybernetics as this science applied to systems control and computer design. The essential components of a closed-loop system are inputs, outputs, and servomechanisms. In psychological models, these components can be defined operationally. Inputs are cues, outputs are responses to them, and servomechanisms represent corrective reactions to negative feedback. Given a cue, a person responds according to the characteristics of the processing loop. All the while, he monitors his actions relative to the system by recognizing indicators of desirable and undesirable effects on system performance. In the case of undesirable effects, the performer's recognition of them comprises negative feedback which, as an additional cue, leads to alterations in responses.

The value of closed-loop models for training is twofold. First, they parallel a variety of behavior. Second, the behavioral concepts--cues, responses, feedback--denote phenomena about which we know a great deal. Moreover, closed-loop models adapt well to what we know about skill acquisition (see later discussions). In fact, Adams (1968, 1971, 1977), a leading proponent of closed-loop theory, titled the main formulation of his position, "A Closed-loop Theory of Motor Learning" (Adams, 1971).

The essence of a closed loop is the functioning of regulatory feedback while an action is occurring. As stated, many skills have this characteristic. However, as an action becomes more and more habitual, the performer is less and less sensitive to feedback during the action. Furthermore, the lack of sensitivity is related to time constraints on performance. Thus, rapid actions of short duration (throwing a ball; sudden discrete control inputs; etc.) do not appear to fit a closed-loop model because there is not enough time to process negative feedback (Hammerton, 1981; Howarth & Beggs, 1981; however, see Adams, 1977). Neither do slower, longer actions that have become habitual to the point of mechanization, or which incorporate no natural provisions for concurrent feedback.

Open-loop models are designed for actions of these sorts. They require only a cue for their initiation and an integrated set of associated responses. Intuitively, it appears that the integrated cue-response system required in open loops must follow a "program." That is, once the cue to initiate an action occurs, the action is executed without internally based interruption just as though it were directed by a computer program that had no error

detector or contingent branching.[1] Feedback, in this case knowledge of results, can be effective only at the end of an action, and then only for a subsequent action.

As with closed loops, we know quite a bit at the gross behavioral level about processes comprising open loops--the development of cue and response discriminations and the effects of knowledge of results. In fact, we know more about feedback as knowledge of results than as a servomechanism. Nevertheless, as presently formulated, both types of loop models suffer a serious limitation. They do not incorporate generalization processes. That is, in postulating single-loop control of a given action, they do not explain how--or even whether--a given learned action can be performed in the ever changing contexts of real-world situations. In other words, one would have to posit a separate loop for each variation in situations, including those not yet encountered. Obviously, loop models cannot account for the critical characteristic of skill robustness as discussed in Section II.

Schema models are attempts to surmount this problem. As with cognitive schemata (Section III), these processing "structures" are inherently generalization systems. Thus they are not substitutes for loop models; rather, they are part of the long-term memory (Laabs & Simmons, 1981) in which loops fill designated roles (Holding, 1981; Newell, 1981; Summers, 1981). In the computer analogy, they are hierarchical executive systems (Section III) in which master and subordinate programs assess requirements of a situation, scan available behavioral resources, and adapt and activate processing units (e.g., loops) as needed. Robustness--discriminative generalization--of skills is thus dependent on the structure of schemata.

We know practically nothing about the development of motor schemata qua motor schemata. Schematic motor processing has not been studied directly to anywhere near the extent schematic cognitive processes have. It is not even clear that they can be as comprehensive as cognitive schemata. General beliefs are that they cannot, but common positions on the issue may be due to failure to conceive of motor performance in a sufficiently broad framework (see later discussion of task specificity of motor skills). At any rate, we do have a backlog of data on training motor skills for generalization. And because motor performance seems more and more to involve cognitive components (schemata are only one example), and to be analogous to cognitive processes, there is hope that cognitive research will clarify issues in motor behavior (Holding, 1981; Laabs & Simmons, 1981).

It may also be that conceptions of motor behavior can help clarify issues in cognitive performance. As mentioned in Section III, cognitive models tend to view people as logic machines, i.e., in terms of purely rational cortical functioning. Estes (1975) and Evans (1980) (and others) emphasized the

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[1] Some writers use "motor program" instead of "open-loop" in referring to these types of models. "Motor program" is more descriptive, for "open-loop" is a misnomer in some usages. The behavior designated often does not comprise a loop in the sense of a recurring sequence of responses in a single action; and the behavior may be "open" only in that negative feedback does not force a return to a starting (input) point to adjust responses.

restrictions inherent in such views. We are just as dependent on lower brain centers as were the "lower" animals from whom we evolved. What was termed earlier a "dynamic" approach to understanding motor performance recognizes that behavior derives from integrative processes of the central nervous system as a whole. In a generalized sense of Mandler's (1962) "functional units" (see Models of Memory in Section III), integrations are governed by task requirements as constrained, of course, by behavioral characteristics of the brain centers involved. In effect, the orientation has much in common with popular conceptions of behavior. The brain is an organ of comprehension, so skills develop and actions are executed via intelligence guided by experience.

Recent attempts to reduce the vagueness of such an orientation have focused on localization of response systems in the brain. However, except for clinically oriented studies (cf. Shingledecker, 1981, for example), these attempts have centered mostly on the cortex (cf. Kinsbourne, 1981; Nebes, 1974). Some of the research is of considerable interest, especially that showing patterns of interference among psychomotor processes to be related to the roles of left and right hemispheres of the cortex. However, the implications of the findings seem to be greater for the design of tasks and operational equipment than for training once task requirements and equipment characteristics are established.

Finally, there should be mention of numerous attempts to develop processing models, mostly minimodels, of a mathematical nature. The earliest, and almost only, comprehensive models were extrapolations from information theory (Gilbert, 1958, 1966; Shannon & Weaver, 1949). This approach received quite a bit of attention in psychology (Attneave, 1959; Fitts, 1954; Hick, 1952; Hyman, 1953; see Johnson, 1967, for bibliography). It was not particularly successful in psychology, however (Howarth & Beggs, 1981), nor in other fields for that matter (Bross, 1966).

On the other hand, minimodels, building on decades of quantitative descriptions of motor behavior as well as recent work, have developed equational formulations that have been quite successful in predicting performance of specific skills, especially discrete movements. For present purposes, the value of these minimodels is their specification of response components leading to errors and sources of inaccuracies in performance. There also have been some attempts (e.g., Restle, 1958; Suppes, Macken, & Zanotti, 1978) to formulate mathematically the cognitive roles of various factors that are amenable to instruction.

## MOTOR ASPECTS

This discussion addresses response production, structural characteristics of movements, and temporal characteristics of movements.

RESPONSE PRODUCTION. Conditions affecting response production, specifically conditions of practice that lead to response stability, have been explored extensively for simple skills. However, as explained in Section III, the mechanisms whereby responses are selected, adapted, and initiated are still largely matters of speculation. Perhaps it is alright in cognitive theories to assume that responses emerge from the information processing matrix. Nevertheless, in motor learning and performance, it seems that the mechanisms

of response production should be a concern. Generally, it is assumed that sets are involved, as indeed they must be, but the nature of the sets, how they come to produce responses, and how response production per se develops with practice are largely ignored. Also, while the implicit processes are not often called such, the sets must incorporate cue and response discriminations and generalizations in order for responses to be selected and adapted. It is recognized, of course, that selection and adaptation occur in motor performance; but there have been few attempts to examine the nature of these processes. Especially lacking is research on long-term development of the governing sets and their retention over time. The bulk of the laboratory work, and of the theorizing, has been concerned with short-term development and memory of (mostly) simple skills.

Nevertheless, there is one approach to theories of skill performance that should help in conceiving of response production in a training setting. Specifically, so-called "motor programs" posit the existence of a functional neural structure in which cue-response relations are "stored." (See Cognitive Aspects this section.) This conception, which is derived from an analogy to computer operations, can be objectionable in that there is no convincing evidence that physiological processes correspond to those of computers. However, "motor program" does have heuristic value; and as Summers (1981) has demonstrated, one need not be bound by the restrictive assumptions made by individual theorists who built on the computer analogy. We will return to this topic later.

An especially difficult question from the standpoint of motor theory concerns the origins of responses. How is it that an individual comes to have a response to select or initiate prior to learning a cue-response relation? Easton (1972) proposed that motor responses are developed using reflex patterns as "building blocks," and Hayes and Marteniuk (1976) showed that reflexes can be chained to form movement patterns that are subject to alterations through conditioning and the intentions of the performer. This approach smacks of the attempts in the nineteenth and early twentieth centuries to explain all behavior in terms of conditioned reflex systems. (One early theorist, J. Loeb, carried the reduction to the level of tropisms. It is not clear that modern theories of neural mechanics are a significant improvement.) Fortunately, the question of the ultimate origins of responses is not of concern in the present project. Rather, the question is how can we design training so as to build on common response capabilities already possessed by learners, whatever their origins?

STRUCTURAL CHARACTERISTICS OF MOVEMENTS. Enough work has been done on the structural characteristics of movements involved in skill performance to reveal the need to understand them. In his doctoral dissertation in 1899, Robert S. Woodworth (cited in Howarth & Beggs, 1981) described three characteristics of movements that have been a major topic for study to this day. Identified as phases of movement, these characteristics are: (1) initial acceleration at the onset of movement; followed by (2) a period of constant velocity; and (3) deceleration of movement as a terminal point is approached. The durations of these phases vary with practice and with purpose. For example, if the movement is to terminate at a particular target, it must be aimed. Woodworth found that when care is taken during aiming, the initial accelerative phase is quite brief, and the decelerative phase is drawn out.

Furthermore, during deceleration, feedback is employed to introduce corrections. On the other hand, unaimed movements (e.g., along a defined distance with no need to hit a target) typically do not show such a marked period of deceleration, nor the use of coincident feedback.

An additional finding by Woodworth (Howarth & Beggs, 1981) was that practice, at least under the task conditions used, had little effect on the target accuracy of very rapid movements but did affect accuracy of slower movements. Beggs and Howarth (1972) showed that the practice effects on slow movements were related to a lengthening of the decelerative phase. That is, subjects spent more time assimilating feedback and correcting errors. (With practice, their subjects moved more rapidly during the first, accelerative phase.)

Woodworth's findings have held up well over the years (Howarth & Beggs, 1981), and there have been several variations on his approach in subsequent experiments. The variations will not be pursued at this time. Rather, this part of the discussion will close by highlighting five major aspects of his findings as confirmed in subsequent research. First, the effects of practice on accuracy of movements appear to have been mediated through increased use of feedback. Second, the increased use of feedback was made possible by performers' own adjustments in the response process whereby feedback cues could be more readily recognized and assimilated (see later discussion of speed-accuracy trade-offs). Third, the differential effects of practice on fast versus slow movements appear to have been due to lack of opportunity to employ feedback cues for corrections during fast movements. Fourth, more effective use of feedback during slow movements was possible because it could be mediated visually. Fifth, a distinction should be made between systematic errors (e.g., the mean of errors taking algebraic sign into consideration) and variable errors (e.g., the mean of absolute errors). Systematic errors tend to be positive (too long a movement) for near targets but negative for far targets, while variable errors are monotonically related to target distance.

When considering the implications of these points for training, one must conceive of skills considerably more complex than the movements studied by Woodworth (and most others studied in laboratory settings). "Accuracy" in everyday life typically involves a matrix of criteria, whether or not performance can be evaluated overall according to a particular fulfillment of task requirements. Also, one cannot arbitrarily force fast or slow movements. The speed of movements is largely determined by requirements inherent in the tasks to be performed and by performers' idiosyncratic adjustments to these requirements (see following subsection). Nevertheless, most skills, including those that require fast movements, in the early stages of acquisition probably function as closed-loop control systems in which performers attend one aspect at a time and attempt to monitor their performance on this aspect while it is in progress. It would be helpful if this natural, if not necessary, inclination could be facilitated by a device that permitted part-task practice of separate temporary closed-loop systems, preferably with the option of switching from one part-task to another according to progress. "Freezing" selected parameters in a flight simulator serves such a purpose. However, one general advantage of simulators that perhaps has not been emphasized enough is that learners can choose to focus on one component skill at a time without danger to themselves or to the equipment. That they do so was evident in a recent exploratory study (Isley & Spears, 1982; Isley, Spears, Prophet, & Corley, 1982) in which Navy pilots practiced simulated aircraft carrier landings.

From computer printouts of percents of time in tolerance during landing approaches, it was apparent that for the first 16-24 trials the pilots tended to concentrate on glideslope or angle of attack (AOA) or line-up, with the particular part-task receiving the most attention varying from trial to trial, and even from one segment of the approach to another. In other words, in spite of the ostensible grounds for positive relations among performances on these three tasks, intercorrelations of percents of time in tolerance were as often negative as positive in earlier trials, becoming predominantly positive only after integrations of the tasks began to develop. (See Organizational Aspects of Skills for a further discussion of these data.)

A different sort of analysis of movements was presented by Smith and Smith (1966). In a series of studies, they, together with colleagues, found three components that are distinguished by their commonality to a variety of movements, their relative independence of each other, their frequently differing rates of acquisition, and their differing transfer characteristics. They termed these components: (1) posture, or the general body attitude relative to a task; (2) transport, or rate control of movements of limbs involved in an act; and (3) manipulation, or contact and positioning movements. Viewing skills largely as closed-loop systems, Smith and Smith considered posture regulated mainly with respect to gravity, transport regulated through neural and learned patterns of feedback, and manipulation regulated through stimulation arising from contact of hands, fingers, etc., with the objects being manipulated. The manipulative movements depend on preparatory transport movements, which in turn are supported by the postural base.

Smith and Smith (1966, p. 414) emphasized that postural and transport movements are not greatly affected by practice because, through daily experiences, they become highly generalized. Postural movements can introduce interference, however, and if so they can be altered with practice (Jones, 1965). As for the lack of practice effects on transport movements, compare Woodworth's finding that rapid transport movements were not affected by practice. (It is interesting to note that, except for experiments on tracking, transport movements have been the ones most frequently studied.) On the other hand, manipulative movements, being the most specialized, not only require more practice for mastery, they are least likely to generalize or transfer to a different context.

On the basis of the degrees of generalization and specialization involved, these points seem defensible as stated. There is also empirical support for them. Hecker, Greene, and Smith (1956) found the predicted differential in the effects of practice on transport (they termed it "travel") and manipulative movements involved in a dial-setting task. Smader and Smith (1953) found similar differential effects in a pin-assembly task. Of special note, however, is the reduction in the differential found by Hecker et al. (1956) as the transport component required more precise, i.e., discriminative, spatial positioning of the hands. A similar, but more revealing effect was reported by Simon (1956). Using the pin-assembly task of Smader and Smith, Simon increased discrimination requirements at various points in the assembly operation (grasping; loaded transport, i.e., with pin in hand; positioning; empty transport). He found that when greater discrimination was required within the positioning component, practice had greater effects on both this component and the grasping component. With the increased discrimination

required in the loaded transport component, this component and the grasping component showed increased practice effects.

Von Trebra (cited in Smith & Smith, 1966, p. 416) demonstrated the complexity of the transfer of transport and manipulative components of movements. Subjects first practiced a sequence of switching tasks using one of four movement patterns, and then were tested for transfer on the other three. Not only did transfer vary depending on the learning and transfer movement patterns, the transfer of transport and manipulative components differed as well, often radically. In fact, of the twelve transfer configurations, manipulation had positive transfer effects on eleven and negative effects on one, while transport had positive effects on only five and negative effects on seven.

On reflection, Von Trebra's data are not all that surprising. Differing patterns of transport movement may be expected to interfere with each other, but not the manipulative movements (switching) because they were essentially the same in all tasks. Yet, it is apparent in the data that the magnitude of manipulative transfer was differentially affected by movement patterns. In other words, an understanding of transfer requires insights into the coordination of actions.

Certain proscriptive implications of this discussion for device training are fairly obvious. Task performance in a device should not involve directions of transport movements that are at odds with those needed for operational equipment. As manipulative movements depend on transport induced positions, device task performance should not require a coordination of these movements that is structurally different from those needed with real equipment. Less obvious is the implication of a need to provide a means for ongoing monitoring of each component of a movement by the performer, both in the device and probably during the early stages of practice with operational equipment. There are other implications, probably more profound ones, that cannot be clarified until temporal and cognitive aspects of skill performance are examined. The same holds for the characteristics of movements identified by Woodworth, so there will be reason to mention these topics again.

In the discussion of Woodworth's data, reference was made to differences in movement patterns when aiming at a target was and was not involved. This difference is probably important, and it leads to another way of viewing components of movements. Specifically, aiming and transport (in the sense of Smith and Smith) are governed by different internal processes. In Woodworth's terminology, aiming is governed by vision and transport by a "muscle sense." Furthermore, aiming is corrected during movement by concurrent feedback as a servomechanism, but after sufficient practice, transport involves minimum use of concurrent feedback. The probable importance of this difference lies in the effects of practice on these components as discussed earlier, and the likely differing conditions that optimize their acquisition. Because of these differences, Howarth and Beggs (1981) pointed to the need to measure accuracy of aiming and transport (not their term) separately so as to reveal their separate contributions to skilled movements. If measured through errors, lack of transport accuracy would be reflected by errors in the direction of movement, and aiming accuracy by errors orthogonal to the direction of movement. These separate measures are of interest not only for research purposes, but for monitoring and diagnosing sources of difficulty during training.

TEMPORAL CHARACTERISTICS OF MOVEMENTS. For complex control skills, temporal characteristics of motor movements are probably the most basic consideration in the conception and design of part-task and low-fidelity training devices. In various ways, timing of responses is the essence of skill coordination; and it is in the timing that interference effects are often most profound. Any training device which, because of its design or manner of use, results in inappropriate timing of responses is likely to produce negative transfer. Furthermore, if practice in the device progresses to the point that inappropriate temporal patterns become well established, the patterns can be very difficult to change (Newell, 1981; Summers, 1975). There is a problem, however, in specifying just what aspects of timing are critical and which are not. This section attempts a clarification of the problem.

It is difficult to assess the adequacy of our knowledge regarding temporal characteristics of motor skills. Certainly, reaction time and harmonic relations among responses are critical to coordinated performance. Reaction times have been studied since the earliest days of experimental psychology, and there is an abundance of literature on the topic. Yet, Castellan and Restle (1978), in the third volume of their Cognitive Theory, devote roughly half of the pages to Part II which is entitled, "New Views of Reaction Time and Accuracy." In their chapter of this book, Pachella, Smith, and Stanovich (1978) stated, "with such an extensive effort of cognitive psychologists centering around the use of this single variable [reaction time], it has become crucial that the variable come under close scrutiny" (p. 169). Pachella et al. were referring to the central role of reaction time as a dependent variable in cognitive research (see Section III). Nevertheless, their point is even more important to psychologists studying motor skills where reaction times are integral to skill performance. It is widely accepted that cognitive processes underlie these skills, so reaction times in cue detection, in hierarchical processing of cues, in response production which is governed by sets, in interpretation of feedback, etc.--all cognitive processes--necessarily govern critical aspects of motor performance.

Although, as stated, it is difficult to assess the adequacy of our knowledge regarding temporal characteristics of skills, we know enough about reaction time, harmonic relations, and dynamic components of movements to shed light on their roles. The bulk of this subsection will be devoted to these topics. Harmonic relations will be discussed first because part of the significance of reaction times is their incorporation into harmonic rhythms.

Harmonic Patterns. Harmonic relations among movements characterize a wide variety of motor skills (Summers, 1981). Although these rhythmic processes as such have not been the object of much study, their existence is easily inferred from interference effects that result when conflicting harmonic patterns are imposed on behavior. For example, Klapp (1979) found that subjects could not rhythmically press separate telegraph keys at the same time with the right and left hands unless the two periods were either the same or one was an integral multiple of the other. Klapp and Greim (1979) found that for certain classes of movements, two movements could not even be executed at the same time if they differed in duration. Summers (1975, 1981) found substantial negative transfer effects when subjects learned a task with one inherent harmonic pattern and then changed to another similar task with a different inherent harmonic pattern. In reviewing these and other studies, Newell

(1981) observed that harmonic patterns in skills can be difficult to acquire and difficult to eliminate. Instead of changing harmonic patterns when integrating movements of differing harmonics, learners are more likely to establish higher order harmonics with which the separate harmonics are consonant. For example, concurrent dual sequences of responses, one with a period of three time units and the other of four, would likely be integrated into a pattern of 12 time units' duration. Considerable effort can be involved in such integrations.

Research in this area is skimpy, especially as it may apply to military training, but perhaps enough has been said to show why harmonic relations among skill components cannot be ignored if one wishes to understand motor skills and their development. The discussion that follows regarding reaction time adds support for this statement.

Reaction Time. The role of reaction time in motor skills is evident from an examination of the complexity of time consuming processes involved in performance. (It also becomes clear why Pachella [1974] cautioned against the traditional over-simplified view of reaction time.) First, we recognize that there are time constraints on responses. They can be too early, but undue delay is the greater training problem. Within the time constraints, a cue must be detected; processing must be initiated, including discriminations of unique cue characteristics and generalizations appropriate to the context; a "memory search" must ensue to relate the resulting cue information to appropriate processing of reactions; a response must be selected and initiated. Once begun, the response must be monitored and adjusted or corrected as conditions and purposes require, which calls for detections of feedback cues and then repetitions of the entire process.

Every step of this process has its own reaction time, and overall reaction time for an action is governed by these delays plus the time required to complete each step. For complex actions involving interdependent simultaneous skills, new temporal dimensions are introduced related to the coordination of reaction times. And the point to remember is that rhythm and timing are based on internal schedules, not response onset (Shaffer, 1982).

Perhaps it is already apparent that training, among other specific objectives, should target schemata--learning sets in the long haul--those ubiquitous states whereby each step in the process becomes predetermined and free from interference. The steps must be habituated to the point that each one, discriminations and all, are automatic, and just as automatically, inappropriate alternative reactions never arise. Apparent or not, it would be well to illustrate a few aspects of reaction time so as to emphasize what is involved in establishing the necessary sets.

We begin with an assertion and then justify it. Certain measures of reaction times reveal important differences between expert and novice performers.

Considering gross, i.e., total response, reaction time first, it is well known that mean reaction time becomes reduced with practice. It is not so well known, or if so not adequately appreciated (Rabbitt, 1981), that practice has perhaps more profound effects on the variability of reaction times. That is, reaction times from trial to trial become more similar with practice, thus resulting in more consistent performance. In complex skills, for which

performers typically develop idiosyncratic harmonic patterns, the reduction in variance of reaction times may well be more critical than rapidity per se. No harmonic pattern can be maintained otherwise. This is one reason expert performance is characterized by consistent quality. A novice pilot can perform a maneuver in an airplane with near perfection on occasion; an expert hardly ever performs it any other way. The expert's consistency would not be possible unless his reactions to controls had consistent timing. In turn, consistent gross reaction times imply consistently timed automatic processing of information through the steps outlined above.

This leads to an important cognitive aspect of response timing. In simple tasks at least, reaction times for erroneous responses are usually more rapid than for accurate responses (Rabbitt, 1981). If learners are provided sufficient feedback regarding accuracy, they generally reach a point at which speed-accuracy trade-offs are at a near optimum as perceived by the learner (Kinsbourne, 1981; Link, 1978; Pachella et al., 1978; Rabbitt, 1981; for mathematical analyses: Townsend & Ashby, 1978; Baird & Noma, 1978, especially Ch. 8). That is, they slow down enough to check discriminations, monitor actions, etc., to the extent they can achieve an acceptable level of accuracy while maintaining acceptable speed. Though admittedly speculative, it is not unreasonable to expect that harmonic patterns originate in these trade-offs, at least partly. If so, speed-accuracy trade-offs habituated in a training device would underlie harmonics of response patterns that would be transferred, for better or for worse, to operational equipment. (Klapp and Greim [1979] might prefer to say that harmonic relations establish reaction times. The preference here is for the priority of speed-accuracy trade-offs.)

Howarth and Beggs (1981) reviewed a group of studies that show another relation between reaction time and accuracy of responses. Because of the requirements of the mathematical analyses and formulations with which they were dealing, they focused on "corrective" reaction time, or that involved in responding to (usually visual) feedback cues indicating errors in movements. Generally speaking, the closer to a target a corrective response occurs, the more accurate the movement to the target. The faster the detection of and reaction to erroneous aiming, the closer to the target a corrective response can be made. Similarly, the slower the movement, the closer to the goal errors can be detected and corrected. Hence the lengthening of the final deceleration phase of the movement that occurs with practice and the increased use of feedback (see earlier discussion of structural characteristics of movements).

Again, there are speed-accuracy trade-offs, with reaction times to feedback cues and of response initiation two central factors. And temporal patterning should result. Overall speed is limited by the duration of the deceleration phase, which in turn must be sufficient in duration for acceptable accuracy of performance, which in turn depends on how rapidly error cues can be detected, processed, and corrective responses made. No wonder harmonic patterns in responses tend to be idiosyncratic. Learners have to organize their reactions according to their own timing capabilities which depend not only on structural neural factors but on ineradicable processing habits (learning sets) acquired over a lifetime. And one governor of the temporal pattern, of the harmonics one eventually makes habitual, is the performer's willingness to err--the speed-accuracy trade-off!

As can be seen, the sets alluded to by theorists to explain cue detection, information processing, and response selection and production are highly complex and idiosyncratic. It is also apparent that magnitudes and variabilities of delays in responding to error conditions can reveal not only achievement levels but the progressive effects of practice. Measures of these kinds would be valuable for research as well as for monitoring training. Furthermore, computers controlling training devices could be easily programmed to provide the measures.

Dynamic Components. The three sequential components of movements described by Woodworth, initial acceleration, followed by constant velocity, and then final deceleration as a terminal point is reached, all are dynamic concepts. That is, they refer to characteristics of motion as a function of time. They were discussed as structural components, however, because the emphasis of so much of the work done on them has focused not on the dynamic properties but on the duration of the components and events related to them--for example, the lengthening of the deceleration component and the corresponding increase in utilization of feedback. The concern of the studies discussed above was not the quantitative dynamic characteristics of these components, the rate of acceleration, the rate of constant motion, the rate of deceleration.

These quantities themselves can be of interest, as well as at least one other, the force of a movement. The reason is the evidence that these dynamic characteristics have transfer properties that differ from those of the structural characteristics. (As the classic work in 1915 by Thompson [1956] showed, dynamic characteristics also prescribe limits for actions.) For example, positive transfer of dynamic characteristics commonly occurs when performance must be "compressed" into a shorter distance or time interval, even though quantitative measures of acceleration, velocity, and deceleration must change. (There are excellent illustrations of such positive transfer involving compressed distances in training with low-fidelity devices--e.g., Cox, Wood, Boren, & Thorne, 1965.) On the other hand, forced changes in the structural characteristics of movements often lead to negative transfer in movement patterns as discussed earlier (Smith & Smith, 1966, p. 416).

Newell (1981) addressed these differences briefly, using a different terminology. (He referred to "metrical" instead of "dynamic" characteristics.) It is not clear which term is preferable, nor even that they distinguish the same properties of movements.

Effects of Situational Factors. To a great extent, temporal patterns in skill execution are driven by time-related factors external to the performer--time constraints on task performance, sensitivity of equipment to inputs, stability of the equipment (e.g., an aircraft) in the operational environment, time of availability of externally arising feedback, etc. Generally, temporal patterning of actions will adapt, with practice, to these various influences. From the standpoint of device training, timing of external feedback is a problem primarily for closed-loop skills, and then only when delays in feedback result in the development of inappropriate rhythmic patterns such as, for example, the jerky, uncoordinated movements reported by Smith (1962) resulting from delayed visual feedback. A similar effect is the prolonged, repetitious enunciations of syllables when auditory feedback of one's own voice is delayed (Yates, 1963). Also, it is well known in the training community that undue

transport delays in simulator platform movements or visual scenes result in "overcontrol" patterns of responses. Corrective responses are made during monitoring of an action, but because of delays in feedback, corrections are maintained too long. The result well may be a pattern of sine-wave harmonic corrections-recorrections more exaggerated than necessary. Recall that once learned, harmonic patterns are difficult to eliminate, and patterns of differing harmonics produce interference.

Even so, realistic delays characteristic of actual equipment, when of sufficient duration--less than a second for some movements--have been found to result in errors. Howarth and Beggs (1981) viewed this problem as a loss of position for initiating a movement (see earlier discussion of Smith and Smith, 1966); at any rate, the value of a "remembered" position has been demonstrated by Kinchla and Smyzer (1967) for visually mediated memory and by Adams and Dijkstra (1966) and Pepper and Herman (1970) for that mediated through kinesthesis. Smith and Smith (1966, p. 373) would also emphasize that the spatial patterning of responses changes with delays in feedback. It follows that initial and periodic positions of body and limbs per se, as preparatory sets, can be factors to account for in the design of training equipment, especially the patterning of successive positions in sequential movements.

Two other situational factors listed above, sensitivity of equipment to inputs and operational stability of equipment, are special cases of time constraints on performance. A major effect of time constraints has already been discussed. They help determine the speed-accuracy trade-offs made by performers, and thus reaction times. In addition, they must affect the development of harmonic patterns, although the nature of the latter effect is not clear. For example, the relative timing of control adjustments in stable and unstable aircraft could well be constant for a given pilot, even though total durations of a complete pattern of inputs differ. The issue is skill robustness in the descriptive sense; the central question, however, is the nature of the robustness. Do pilots adapt the relative timing of response components, resulting in different basic harmonics, or do they retain the internal relations among components and expand or compress the total duration as control maintenance requires? The answers to this question have implications for the design and use of part-task devices where only a portion of the response components are represented, and for low-fidelity devices whose functional characteristics might impose time constraints that differ from those found in operational equipment. If device training results in harmonic patterns whose relative timing of components is inappropriate, negative transfer could be expected. As stated, positive transfer would be likely if only durations of intact patterns vary, i.e., only "compression" is necessary.

## PERCEPTUAL ASPECTS

Perception, the process of giving meanings to sensations, is inherently cognitive in nature. Thus, discussion of perceptual aspects of skills separately from their cognitive aspects entails quite arbitrary distinctions between these domains. For present purposes, the distinction amounts to this: a skilled performer must recognize the conditions and need for an action, identify signals indicative of specific actions, and produce the actions and monitor the results. By "perceptual aspects" is meant those processes involved in signal identification, both prior to action initiation and during

monitoring. Excluded from immediate interest are the host of processes that comprise cueing properties for signals, subsequent "memory searches," and response production.

This section discusses three topics in this regard: (1) discrimination of signals; (2) generalization of signal discriminations; and (3) roles of sensory modes.

DISCRIMINATION OF SIGNALS. For present purposes, the importance of signal discrimination is two-fold: the process develops according to fairly well understood principles of discrimination learning; and the status of signal discriminations is amenable to measurement.

It is not necessary at this time to examine principles of discrimination learning applicable to perceptual skills. These principles will be drawn upon at length when training implications of skill analyses are developed. It should be pointed out, however, that the complexities of military skills pose a challenge in the adaptations of these principles to military training. Fortunately, it is a challenge that well designed training devices can meet once we know how to zero in on the discriminations involved.

The importance of the second topic just mentioned, the amenability of signal discriminations to measurement, rests in the need to zero in on the discriminations. Within the formulations of statistical decision theory and signal detection theory, quantitative estimates of "distances" of signals from "noise," or among different signals, can be derived independently of other cognitive processes such as interpretations of signals and resulting responses. Furthermore, through computerized monitoring of ongoing skill performance, these estimates should be obtainable during performance of realistic skill complexes in training devices. There is no need to resort to traditional psychophysical techniques which, as a rule, would require artificial simplified contexts for measuring discriminations. (In addition, while measuring discriminations, statistical decision theory and signal detection theory permit the quantification of certain classes of cognitive processes. For some research purposes, and for diagnoses of learning difficulties, these separate kinds of data can be important.) Then, there are a host of techniques for scaling discriminations which can be quite valuable at least for research purposes. Whether as dependent or independent variables, discriminations can thereby be related more specifically to other variables.

There are a number of excellent reviews of statistical decision theory, signal detection theory, and related scaling techniques. In addition to the general reviews presented in their books, for example, Baird and Noma (1978) and Castellan and Restle (1978) list numerous references to intensive reviews of the several aspects of these topics.

A worthy research effort would be to formulate uses of these quantitative techniques in a way, and within a context, that makes them applicable to device training and research. The effort should include a review of research in which the assumption of an "ideal observer" is evaluated. Both statistical decision theory and signal detection theory postulate certain unrealistic characteristics of those who discriminate signals. Fortunately, accumulated evidence shows that the assumptions need not be as restrictive as convenient mathematical derivation of the theories required.

GENERALIZATION OF SIGNAL DISCRIMINATIONS. There are so-called "closed skills" (Poulton, 1957) that can be performed under relatively invariant conditions, and "open skills" (Pew, 1974) which require continuing adaptations to changing conditions, either from one occasion to another or during a single occasion. (Closed and open skills should not be confused with closed and open loops.) Except for interference effects during training and retention, generalization is not a significant problem for closed skills. It is, however, for open skills where robustness is necessary. Therefore, it would be well to discuss generalization of signal discriminations within a context where robustness is critical. The utilization of feedback during skill performance provides such a context, so we begin by reviewing a few points concerning feedback.

Keele (cited in Summers, 1981) identified four functions for feedback during skill performance. First, it provides information regarding certain initial conditions (e.g., adequacy of preparatory body positions and movements). Second, it is the means for progressive monitoring of performance, for ascertaining whether or not performance is within tolerance. Third, feedback is the basis for "fine tuning" of skills according to the particular conditions for their performance. These fine adjustments may be indicated at the initiation of an action as well as regularly throughout the action. Fourth, feedback determines the course of subsequent development of a skill.

With due precautions regarding the reification in the analogy, the notion of a feedback "template" (Keele, 1973; Keele & Summers, 1976) is a good way to view generalizations of signal discriminations. To adapt these discriminations, the performer should have a "criterion template" with which he can compare feedback signals, thereby identifying feedback that is, and is not, consonant with indications of proper performance. The template requires adaptation to the actual conditions of performance, which for a novice should entail deliberate analysis of what feedback should look, sound, or feel like for particular conditions. With practice under sufficiently varied conditions, the analyses and adaptations would normally become largely automatic.

As reviewed by Keele and Summers (1976), there is considerable evidence that skilled performers act as though they use feedback templates. Bower (1975) considered perception generally a predictive or anticipatory set. That is, consciously or not, performers expect feedback to occur in specific forms and patterns, and adjust actions accordingly. From a training standpoint, students should be taught the sets comprised of such expectancies. They should learn to predict "what happens when," and to recognize when they are correct and when they are not. With conscious predictions specifically targeted as interim objectives, and given realistic variations of circumstances (including specific types of equipment) for performance during training, learners would be forced to practice generalizations of the discriminations involved, and to the point that the corresponding anticipatory sets became automatic according to particular response strategies (Schmidt, 1968).

For many skills, it is important that the expectancies and the derived behavior become rapid and automatic. This can require complex processing. The reaction time to kinesthetic feedback is generally thought to be of the order of 100msec (Glencross, 1977) and the time between successive movements for some skills is of the same order, if not briefer. How does an operator react rapidly enough for smooth performance? One seems forced to the conclusion

that expectancies regarding feedback patterns for such skills relate to overall, idiosyncratic harmonic patterns of skill "units" defined by the individual performer. He seeks, in other words, patterns of feedback units to correspond to patterned units of movement. If so, he probably learns to key on certain components of both feedback and movement patterns, the information from which can be assimilated in the time available. Although they stated it somewhat differently, this hypothesis was proposed by Adams[1] (1968) and Schmidt (1971). If valid, it is one way to account for the obvious fact that feedback functions in some manner even during very rapid actions (Glencross. 1977; Summers, 1981).

ROLES OF SENSORY MODES. Several references have been made to roles of sensory modes in motor performance, and other roles can be readily inferred from discussions. In Smith and Smith's (1966) analysis of movements, for example, the postural component of movements is oriented to gravity which involves vestibular sensations. (It can be added that initially, vision and often tactile sensations are also bases for postural orientation.) Transport movements are guided visually and kinesthetically. Manipulative movements involve tactile senses, and often vision. Harmonic patterns of movements require proprioception, especially kinesthesis, with regular feedback of a tactile nature.

A detailed knowledge of these roles is probably not needed for present purposes. Rather, in line with the criteria stated earlier for selecting topics to discuss in this section, the primary interest is how roles develop and change with practice, and the transfer characteristics of different sensory modes.

As for the development of roles, the earlier discussion of what is involved in acquiring signal discriminations is relevant, as well as the analysis of cue development in Section II.

Changes in Roles. Changes in roles of sensory modes warrant a little more comment at this time. As skills develop, the utilization of feedback to monitor performance often changes. In many cases, a change in the sensory nature of the feedback occurs as well. For example, most transport movements of limbs and manipulative movements of hands and fingers are guided visually in the early stages of skill acquisition. Later, kinesthetic and tactile senses take over. A question of import for the design of training devices is how can provisions be made for visual monitoring early in training that would most effectively ensure the eventual utilization of kinesthetic and tactile feedback? Stated more generally, how can devices be designed to provide feedback so that what is learned via one sensory mode aids in the process of learning to use other sensory modes for the same purpose? More on this a little later.

A related issue is especially pertinent to the use of low-fidelity training devices. Suppose that because of lack of dynamic fidelity, learners must

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[1]However, Adams (1977), holding out for a closed-loop model even for rapid actions, reviewed evidence that reaction times as brief as 10msec might be common.

depend on visual cueing, including feedback, for responses that eventually should depend on proprioception. How long can a learner practice with the device without coming to depend unduly on the artificial cueing? To the extent that artificial cues function as augmented feedback, there is evidence that performance can become dependent on the augmentation, and if so the effects of practice might dissipate when it is withdrawn. On the other hand, when augmented feedback is closely related to natural feedback such as would be the case when resistance of a control to displacement is increased, the augmented feedback can enhance both timing and anticipatory components of sets that govern performance (Glencross, 1977). Furthermore, artificial cueing could be viewed in terms of cue distortions, as would be the case with low-fidelity cueing in general. What is the effect of distorted cues, especially feedback, on learning, performance, and transfer of movements? Smith and Smith (1966) reported a complex study in which directions of star-tracking movements were varied as well as the visual orientation of feedback. They stated, "When we realize that more than eighty significantly different performances were induced by thirty-two combinations of visual orientation and movement direction, we begin to appreciate the countless possibilities for specific space-structured sensory-feedback interactions that might exist under ordinary conditions of behavior" (p. 419). Smith and Smith went on to review studies of effects of visual distortions ranging from vertical inversions to lateral displacements. As is well known, subjects usually adapt to these distortions. They also may retain the adaptations with little or no decrement for at least two years without intervening practice (Snyder & Snyder, 1957). However, Smith and Smith (1966, p. 421) believed that learning occurring under the conditions of distortion is specific to the motions and feedback conditions involved. We will soon return to this topic.

This discussion could be expanded by exploring effects of distortions of cueing through other sensory modalities, especially kinesthesis. However, it is more pertinent to present purposes to point out possible resolutions of the difficulties that can be involved in cue distortions. First, during training it may at times be better to provide cueing through an entirely different sensory mode than to resort to distortions in the actual modality normally used, for example, an aural cue for approaches to operational limits of equipment rather than unrealistic changes in instruments that are interpreted visually. A second way to resolve the difficulties would have a more general value. In Section II, emphasis was placed on the topological characteristics of cues, such as apparent convergence of parallel lines at a distance, as opposed to realistic representations of highways, power lines, etc., that can show convergence. In this light, the depth cues provided by simulated checkerboard ground scenes are not necessarily distortions of reality at all. What we need is a comprehensive analysis of topological characteristics of cues, at least for those provided through vision, kinesthesis, and perceptions of acceleration. The question then would be, how much distortion in topological characteristics can be tolerated? The answer may well be, "not much." (Cf. earlier reference to effects of transport lags on temporal patterns of responses, and on the nature of the movements themselves.) This answer may pose no problems for many purposes, however. As with the checkerboard, critical topological properties may be comparatively easy to represent without distortion.

Intersensory Transfer. Reference was made earlier to intersensory transfer as a process of learning. Specifically, cues from one modality such as vision

can guide the learning of cues related to other sensory processes such as kinesthesis. Phenomena of this sort are observed regularly during training, and they are surely involved in some of the changes in movement patterns as discussed under motor aspects of skills.

Intersensory transfer has profound effects on behavior, and it would be well to view it in a broad perspective. In 1709 the twenty-four-year-old George Berkeley, later Bishop Berkeley, published "An Essay Toward A New Theory of Vision" (Berkeley, 1948). The purpose was to show how vision develops spatial properties by associating retinal images with sensations of muscular movements. This paper became a cornerstone of modern empirical associationism. While there are disagreements as to the primacy of kinesthesis--some would say that visual space lends cognitive spatial properties to movements--numerous studies have confirmed the essential thesis that information from one sensory mode affects the development of interpretations of information from others (e.g., Gesell, Ilg, & Bullis, 1949; Rock & Victor, 1964; Rock & Harris, 1967; Hein, Vital-Durand, Salinger, & Diamond, 1979).

This broad perspective can help avoid misleading interpretations of some aspects of intersensory transfer as it has been studied in skill performance. Specifically, it keeps life-long learning sets in the forefront when considering what are ostensibly highly situation-specific instances of intersensory transfer. As explained below, it also helps account for certain empirical data that appear to be without explanation as currently viewed in skill learning.

Studies of adjustments to distorted visual feedback, discussed earlier, are a case in point. It was found that subjects can adapt quickly to lenses that give visual inversions or left-right reversals (see review of studies by Smith and Smith, 1966, p. 419f); that these adjustments are retained without decrement for at least two years (Snyder & Snyder, 1957); and that they depend on the subjects' associating movements with the visual feedback involved (Smith & Smith, 1966, p. 421). We add two other points. First, it has been clearly established in these studies that subjects can readjust to normal visual feedback very quickly. The significance of this point seems to have been overlooked; it should not be when considering the value of low-fidelity training devices, because negative transfer due to a poor visual simulation may well be only transitory. Second, in contrast to earlier beliefs, Snyder and Snyder's (1957) results showed that a subject can switch back and forth between distorted and normal visual fields without affecting the adjustment to either. This phenomenon should have been obvious to anyone experienced with a microscope, but it was thought that a subject had to wear the distorting lenses all the time to adjust to them. At most, differences between visual (and perhaps other sensory) characteristics of devices and actual equipment would probably have only temporary effects on performance with either type of equipment.

These phenomena can be possible only if derived from highly generalized, highly discriminative, transfer systems. And their empirical characteristics are precisely those of learning sets.

A related aspect of intersensory transfer that has been studied in skill performance is termed "recalibration" (Howarth & Beggs, 1981). This, too, is a process whereby cues from more than one sensory source interact to affect the

informational content of one or more of the other cues. As the term implies, subjects appear to adjust the metric of one (or more) sensory modes so as to gain consonance among originally disparate information from multiple modes. Studies of recalibration have found the process to be quite rapid, situation-specific, and dependent on active movements. In addition, certain questions regarding transfer of positional movements were raised. Howarth and Beggs (1981) discuss these questions, and the transfer difficulties appear to be due to forcing highly situation-specific recalibration. If this is the only problem, it need not concern us.

As with other topics discussed in this section, this is not the place (nor time) to explore the ramifications of intersensory transfer for device training. Suffice it to say that the foregoing discussion focused on robustness of cueing processes, a necessary component of skill robustness; and that by capitalizing on related life-long learning sets in students, part-task and low-fidelity training devices can utilize existing complex discrimination systems to promote skill robustness while ensuring transfer of device training in cue processing to operational equipment. However, it should be apparent that transfer will not generally be observed on the earliest trials with actual equipment if there is much difference in overall cue patterns. One should expect adjustments to the new (operational) patterns first. At least, the adjustments should be rapid with a minimum of residual interference, whether going from a device to actual equipment or vice versa. Minimal interference is one blessing of the specificity of the adjustments to specific cue patterns. It is important, of course, that habitual processes of intersensory transfer be tapped, and that conflicts with habitual processes be avoided.

## COGNITIVE ASPECTS

Although they frequently alluded to cognitive processes, the preceding discussions in this section focused on more or less mechanical, reactive aspects of skill performance. Within traditional S-R theory in psychology, the analysis of motor skills could well end at this point. According to modern thinking, to stop here would be to ignore one of the most important aspects of skill performance. In citing the position of C. Kelley in his 1968 book, Manual and Automatic Control, Moray (1981) stated, "Kelley argues forcefully that the whole aim of control and all behavior associated with it is not to compensate for the present state of affairs, for present or past error, but is directed towards control of the future state of the system" (p. 32). This statement implies that the performer has a goal, i.e., the future state of the system, and that he can organize his behavior so that the goal can be achieved within the constraints of the system. In brief, behavior is purposive, and it involves comprehension pursuant to the purpose.

In these regards, two functions of cognitive processes are discussed, establishment of strategies and execution of actions. A third, verbal formulations, are often mentioned, but the reader is referred to Section III for a fuller discussion of language in information processing. Facets of the topics below have already been discussed in this section and in Section III, so the treatments that follow are sometimes brief.

ESTABLISHMENT OF STRATEGIES. This subsection addresses three topics: (1) goals and standards of performance; (2) planning performance; and (3) information processing strategies.

Goals and Standards for Performance. A strategy implies a purpose, which in turn implies a goal. Goals for skill performance in the military are set forth in training and operational manuals. However, it is not often recognized, at least formally, that there are idiosyncratic facets to goals, especially as related to standards for performance, that are not covered in official statements. Speed-accuracy trade-offs, which have already been discussed, are one such facet, and apparently an important one. A related facet, which we simply dub "facilitation trade-off," an idea close to the "utility consideration" of Navon and Gopher (1979), is often a topic of discussion among the writer and his colleagues. We have noticed on several occasions that thoroughly experienced pilots can have trouble during formal evaluations meeting specific official performance criteria for various maneuvers, even if they have been performing the maneuvers regularly for a long time. Often viewed as a problem of retention, it would sometimes be more appropriate to consider these difficulties as imposed by the criteria themselves. It is not that the pilots cannot perform the maneuvers, and skillfully; rather, during long hours of self-guided performance they have developed their own standards for how the maneuver should occur. There is a difference between the nature of performance deviations on thoroughly practiced maneuvers and discrepancies on those that have been performed only rarely. The latter maneuvers show true, often dangerous loss in ability to achieve the purpose of the maneuvers; the former reflect purposive departures from official criteria, departures that may be as safe as the standards. In making these departures, the performer has simply facilitated idiosyncratic performance.

This is not to justify the idiosyncratic aspects in such an instance. There are good reasons for standardizing the performance of flight maneuvers--for formation flight for example. However, perusal of some military maintenance manuals, or discussions with maintenance personnel, can reveal how arbitrary standard criteria for adequate performance can sometimes be. Without taking a stand for or against standardization, we simply point out that performers will make facilitative trade-offs where possible. The trade-offs often follow from idiosyncratic characteristics of performance such as harmonic patterns of responses that underlie a given individual's skill. Furthermore, the trade-offs develop along with skill mastery. An expert feels less bound to externally imposed standards than does a novice.

This modification over time of criteria for adequate performance is common (Hammerton, 1981). Sometimes it is for the worse. Experts can become sloppy performers when there is no need to be otherwise. But thinking of the skill "decay" as a problem only of retention can be misleading. The degradation of performance in this case would result from compromising standards. In view of the fact that self-set standards for performance are more enduring than those externally imposed, and that performance to self-set standards is retained longer (Laabs & Simmons, 1981; Locke, Shaw, Saari, & Latham, 1981), it is important that military standards be taught in a way that they become incorporated into the value system of the performer at the outset. It is also important that the goals be specific and, to the learner, challenging (Locke et al., 1981). An obvious implication: a training device that can be "pinballed," and a training atmosphere that allows pinballing to occur, will at best delay opportunities for many students to set realistic standards for quality performance. At worst, idiosyncratic standards will be adopted that

will result in negative transfer in the short term, and in an attitude that could have later, enduring effects on performance. (A moment's reflection will reveal that what is often called a "poor attitude" in performers amounts largely to their inadequate personal standards for performance.)

A related point concerns training devices that, because of low fidelity or incomplete provisions for a task, do not allow for performance to a desirable standard. It would be important that, when such devices are used, the tasks covered during practice be restricted to those for which desirable standards could be communicated verbally, thus maintaining at least a cognitive basis for later discrimination of standards.

Planning Performance. The planning of task performance is usually thought of in terms of deliberate, conscious efforts to bring cognitive processes to bear on skills. In basic behavioral terms, the planning is to develop immediate and contingent sets for cue discriminations and interpretations and for response selection and initiation. Deliberate analyses of the peculiarities of given situations are to guide adaptations of the processing of this information, including expectancies (templates) regarding the nature of feedback during performance. These aspects were discussed at length in Section III.

By design at least, military training and operational procedures provide extensively for these deliberative aspects of task preparation. In practice, the planning is sometimes slighted, perhaps most often in preparing students to derive maximum benefit from training devices. Caro et al. (1981) discussed this neglect in the use of aircrew training devices from several different standpoints and explained how careful planning by the instructor, and judicious use of device training features, could enhance device success. Their points need not be reviewed here. Suffice it to say that the implications of their recommendations extend to training all skills.

Of more immediate concern are the nondeliberative aspects of planning. These largely unconscious processes are, if anything, probably more fundamental to motor skill performance than the deliberative aspects. Of special importance are the recalibration of cues, establishment of cue expectancies (recall from Section II that cues as defined imply actions), and the establishment of feedback templates. The ramifications of these factors, all components of sets that govern action, extend beyond task planning into the execution and monitoring of actions. The more general role of recalibration of cues was discussed under Intersensory Transfer. The other two topics are treated later under Execution of Actions.

Information Processing Strategies. During the early stages of skill acquisition, performers seem to process information regarding individual skill components independently of that relating to other components. Depending on skill complexity, they may even ignore several components at any given time (e.g., the focus on glideslope versus angle of attack versus line-up by navy pilots discussed earlier). With practice, joint processing develops, apparently with complex hierarchical relations among cues, response contingencies, monitoring sequences, and other foci of attention. The result is a dependence of skill coordination on the integrity and adaptability of entire hierarchial processing schemata.

Very little is known about schemata as they actually function during performance of motor skills. Reference is often made to "motor programs" but little is said about their functional structure beyond analogies to gross characteristics of computers. Research has established, however, that processes corresponding heuristically to these notions do exist (Summers, 1981).

There is one area related to strategies of information processing that has been investigated to a considerable extent, albeit with a restricted focus. Certain aspects of these studies were discussed earlier as signal detection theory and statistical decision theory. It was pointed out that with these approaches, signal detection could be mathematically separated from signal processing. In doing so, signal processing is often reduced to "likelihood ratios" (Baird & Noma, 1978), which are bases for computing speed-accuracy trade-offs or response probabilities.

A related topic, stimulus encoding, has also been the focus of several studies of motor skills, but the concept is not as well integrated into motor performance as it is in cognitive skills. It was discussed at length in Section III, so for present purposes, "encoding" will refer simply to cue discriminations. It is clear that encoding strategies--i.e., the process of discriminating cues--can change with practice. Rabbitt, Cumming, and Vyas (1979) noted that their subjects acquired hierarchical processing patterns for identifying target letters mixed with distractor letters. From an original strategy of considering each target letter an independent event, they developed a two-step process in which a letter was first identified according to its class (target or nontarget), and then as a particular letter of the target class. The greater the complexity of a skill, the more significant such changes should be. Complex skills include numerous cues, and on logical grounds it can be expected that hierarchical processing will result in more rapid cue discriminations than a serial cue-by-cue search of memory would. Rabbitt (1981) especially stressed qualitative changes in encoding strategies that occur with practice: "subjects do not simply retain and improve the same strategies of signal recognition, but rather develop new and more efficient ways of dealing with particular discriminations" (Rabbitt, 1981, p. 160; see also Schmidt, 1968).

Of particular present interest are studies of verbal factors in encoding. To a certain extent, these factors appear to parallel the hierarchical organization of the process, if indeed semantic organization is not on occasion the basis for the hierarchical organization. Furthermore, semantic organization can be taught. For better retention, it sometimes appears that learners should be encouraged to provide their own labels (Laabs & Simmons, 1981) rather than to have them imposed, but this may not hold true for all aspects of complex cue systems. At any rate, learners often need help at least for sorting out the major classes of cues.

With appropriate verbal guidance, part-task training devices can aid in the sorting process. The part-tasks should probably involve subsets of cue-response systems that would eventually acquire their own hierarchical organization more or less independently of the organizational relations of the subsets themselves to other subsets not represented in the part-task device. However, it seems that care should be taken not to mix cue-response systems indiscriminately during part-task training. It may delay or even prevent

their hierarchical organization, or worse, lead to organizations that are inappropriate for full-task performance.

One more characteristic of efficient information processing strategies should be mentioned. The schemata involved should include definite "if-then" expectancies. Performers should be able to predict the results of their actions, or of equipment functioning, in the sense that they can anticipate what will follow from a given control input or state of the equipment. The anticipation not only implies knowing what should be done and how; it also permits keying on selected components of feedback patterns and response initiation processes. As pointed out under Temporal Characteristics of Movements, reaction times to individual cues cannot be rapid enough for some actions. There must be a means of using certain cues that appear relatively early in a sequential action to initiate movements that are not due until later. (For rapid movements, "early" and "later" may be separated by only a fraction of a second.) A significant part of any efficient information processing strategy is an habitual set to anticipate and respond accordingly; and when motor skills are involved it seems to be the anticipation that leads to efficient timing of response patterns (Schmidt, 1968, 1971).

Such sets are necessarily complex. They involve temporal control of sensitivities to cues, which vary with expectancies, and adjustments of speeds of reaction times to anticipated harmonics or other temporally governed occasions for responses (Rabbitt, 1981). Furthermore, the sets must remain flexible throughout response execution.

As is well known in the training community, understanding one's performance requires the ability to predict what will follow from control inputs or the status of equipment. Instructors often require students to make such predictions as a way of teaching understanding, and a variety of training equipment includes features to facilitate this instructional practice. Perhaps, however, there has not been enough emphasis on the automatic, nonconscious expectancies that must develop for many sequential actions that require rapid follow-throughs or adjustments. Clearly, these expectancies must be habitual to the point motor actions progress automatically (Keele, 1968), so any training technique or equipment that fosters such habituation is to be desired.

EXECUTION OF ACTIONS. The execution of skilled actions derives largely from cognitive strategies and the motor mechanics of the movements involved. There are also continuing monitoring of actions, and adaptations of movements and of strategies that are indicated during monitoring or as conditions for performance evolve. All of these aspects have been discussed, some more than once. However, a few additional comments are in order regarding two topics: (1) motor programs and schemata; and (2) monitoring of actions.

Motor Programs and Schemata. The purpose here is to provide perspective for earlier piecemeal discussions of motor programs. First, motor programs can be, and often have been, viewed as mechanical systems that incorporate little if any concurrent feedback. Once activated, they progress to completion, influenced only by forcible disruptions from external circumstances. There is an obvious logical difficulty with such a conception when it is applied to skills that can be performed in varying conditions. One must posit a separate

program for every condition in which performance does, or could, occur--in short, an unlimited number of programs for each adaptable skill. Where do all these variations come from? A less obvious difficulty, but according to the evidence just as real (Adams, 1977; Summers, 1981), is the fact that feedback does affect the execution of even very brief, very rapid, seemingly fully automatic movements such as throwing a ball.

Schemata have been postulated to take care of both difficulties, and in doing so invokes definite cognitive control of motor programs. As with cognitive skills, a hierarchical schema for a given action determines a particular strategy, establishes standards, adapts encoding of information and feedback templates, and adjusts responses to the requirements of a situation. With these preparatory adjustments, a motor program then takes over. Instead of an unlimited number of programs for each skill, there need be only a few at most, perhaps only one, to be "edited" by higher-order schematic processes. Further, the higher-order processes "constitute an executive control system that is feedback dependent" (Glencross, 1977, p. 25), thus accounting for the effects of feedback even on brief, rapid movements.

Nevertheless, a qualification is needed if motor programs and schemata are to be useful training concepts. A rigid separation of schemata from motor programs can have restrictive, probably implausible implications. For example, one might conclude that, being dependent on schemata, transfer of motor skills is essentially a cognitive process; or that interference from nonexternal sources is purely a cognitive matter. As important as cognitive processes are for transfer of motor skills, this seems to go too far. (See discussion of difficulties of separate linguistic and experiential LTMs, Section III.)

Similar criticisms could be leveled at training implications of separate schemata and motor programs. However, the point is that a rigid separation of schemata and motor programs should not be attempted in the first place. Of more practical concern in training are the functional characteristics of behavioral organization. At times, it may be desirable to view schemata as programs, or vice versa, or to ignore the concepts entirely. The critical issue for such decisions is the importance for given purposes of focusing attention on mechanical aspects of skills, the role of feedback, specific generalizations that lead to skill robustness and transfer, or mechanisms whereby sets or learning sets affect performance.

Monitoring of Actions. An obvious fact about the execution of an action is that sensitivities to and interpretations of cues vary with progressive stages of the action. In many instances, these changes result from a need to fine-tune feedback templates to the requirements of particular conditions that were not clearly anticipated at the outset. Experts typically make such adjustments quickly and with a minimum of deliberation. On the other hand, novices may need at least brief periods for deliberative analyses of conditions, as well as a night to "think it over" following an insightful debriefing by an instructor. Training devices can allow for deliberation as needed; and properly designed, they can provide varied enough conditions to force the need for, and thus practice of, the process.

Of equal concern are the changes in cue sensitivities and interpretations that should follow the natural evolution of an action. What one should attend from stage to stage depends on the stage. The good instructor guides the student in this respect: "When beginning, you need to watch for A, B, and C. Then, at this point, notice this change in C as well as D and E. Finally, when you are about through, check the status of X, Y, and Z."

Such successive cognitive encodings can be enhanced with training devices that permit cue augmentation and signals to alert the student to feedback conditions he may not be noticing. In some instances, dependence on memory and other cognitive processes can even be increased during early training with part-task and low-fidelity devices. Forced mental rehearsal (Wheaton et al., 1976; Glencross, 1977) of what should happen, how one should recognize it, and what one should do about it is perhaps the most efficient way to crystalize this aspect of performance strategies.

## ORGANIZATION OF MOTOR SKILLS

Two topics discussed under this head, integration of skills and hierarchical organization of skills, address, respectively, the process of acquiring skill organization, and an important characteristic of skills that have been organized. Theories of cognition (Section III) incorporate these topics deliberately; theories of motor behavior have hardly addressed them. Two other topics, the effects of interference and the effects of fatigue, focus on factors that can lead to disruption of skill organization.

INTEGRATION OF SKILLS. Integration of a complex motor skill involves conjoint, precise functioning of numerous motor, perceptual, and cognitive processes. Members of the training community appear to have good, perhaps considerable intuitive knowledge of what is involved, at least in a general sense. However, there has been no concerted effort to analyze the process of complex integrations. Most logical and empirical analyses have focused on simple skills as observed in laboratory settings. Even then, with relatively few exceptions (e.g., Pew, 1966), the process of integration has not been the object of study except in restricted areas such as signal detection. Models derived from most other studies address performance of existing skills, not their acquisition. In fact, in much modern work on motor skills, experimenters do not even start collecting data until subjects have practiced enough for performance to stabilize. Whatever new integrations were involved had already occurred.

Earlier analyses in this section identified a number of skill components that must become integrated for the performance of complex motor skills. In addition, numerous factors, conditions, and basic behavioral processes that determine or otherwise affect the nature and progress of integrations have been discussed. Because of the urgency of everyday training problems, it is tempting to throw caution to the wind and construct a speculative model for the acquisition of skill integration, derived from the characteristics of the behavioral components and processes.

There are alternatives, however. First, the implications of these analyses are of considerable import to training with or without a comparable understanding of how students finally "put it all together." A second

alternative is the development of a methodology for actually observing the status and progress of skill integration. An adequate methodology for this purpose which could be adapted to any motor skill would dispense with the need for a theory of integration. Although a systematic methodology obviously is not represented in them, three examples will illustrate the feasibility of one.

Data from Martin and Waag (1978) provide the first example. Two groups of subjects flew training sorties, ten by each subject, in the Advanced Simulator for Pilot Training (ASPT). One group experienced platform motion and the other did not. The performance of each group was rated on various tasks by instructor pilots (IPs) during five of the trials. The data points in Figure 1 represent mean ratings for each group on an overhead pattern. The points are connected with straight lines to provide a contrast with Figure 2 where solid curves, fit by the least squares method, are shown representing the logistic equation,

$$Y = \frac{h}{1 + ge^{-kx}} .$$

Bearing in mind that the IPs used a 12-point rating scale, and that the highest mean rating for either group was 6.56, what do the curves in Figure 2 suggest that is not apparent in Figure 1? First, it appears that the patterns of data may well say more about the effects of motion than the data points per se can reveal. The curve for the motion group is still rising on the fifth evaluated trial, while that for the no-motion group is not. The asymptotic level A for the motion group, computed from the above equation, was 8.97, but only 6.36 for the no-motion group.[1] The indications are that the motion group, in spite of lower average performance, could have continued to improve well beyond the plateau reached by the no-motion group.

Second, it appears that progress for the motion group was delayed because they had to integrate the motion cues into the skill pattern. There was probably some interference at the outset, but assimilation eventually occurred. This inference is supported by examination of the inflection points for the curves. (The inflection points are the X [trial] and Y [rating] values, Px and Py, respectively, at which positive acceleration of either curve ceases and the curve becomes negatively accelerated; see Section V.) While basic information is first being integrated, a learning curve typically has positive acceleration, with negative acceleration thereafter. For the no-motion group,

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[1] To illustrate how As do not depend unduly on the nature of the equation used, the data were also fit using the radically different Gompertz function,

$$Y = hg^{kx} .$$

Essentially identical curves were obtained, and the As were 9.08 and 6.38 for motion and no-motion groups, respectively.

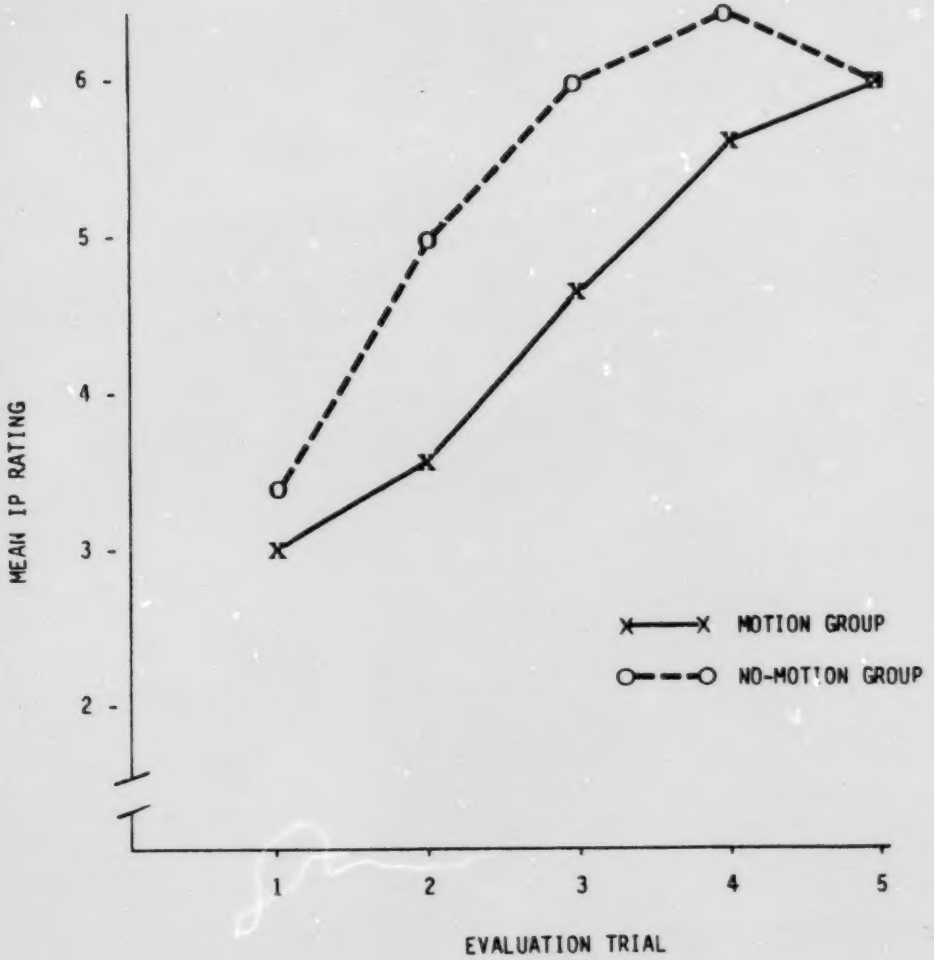


FIGURE 1. PERFORMANCE ON THE OVERHEAD PATTERN IN THE ASPT (DATA FROM MARTIN & WAAG, 1978).

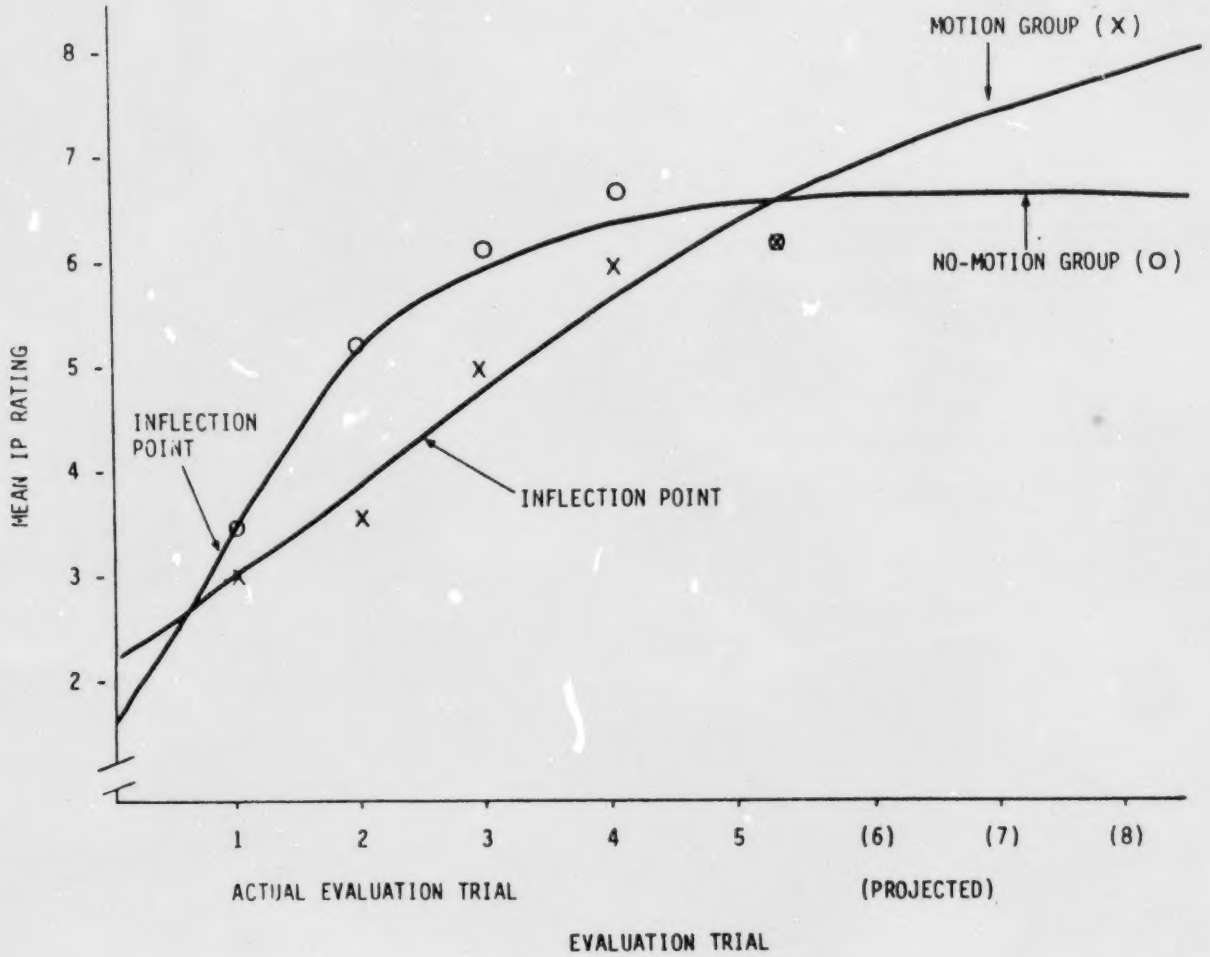




FIGURE 2. SAME AS FIGURE 1 EXCEPT THAT CURVES REPRESENT FITS TO LOGISTIC EQUATIONS.



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Px = 0.90, while Px = 2.78 for the motion group. These are equivalent, respectively, to Pys of 3.18 and 4.48. The inference is that (1) the motion group used motion cues; (2) it took them more trials to integrate the additional information; (3) once assimilated, the motion group was at a higher level of performance than the no-motion group at the time of their assimilation of cues available to them; and (4) the additional motion cues may have resulted in a higher level of performance had practice continued. (Data not discussed here indicate that A can be highly predictive of continued performance; see Section V.)

A second example, taken from Smith, Waters, and Edwards (1975), illustrates a quite different process of assimilation of information, one involving the direct effects of cognitive processes. They gave one group of student pilots intensive cognitive pretraining to aid in recognizing flight segments and landmarks, while a control group had only "normal" instruction. Figure 3 shows logistic curves fit by least squares to the mean number of flight segments recognized on each of the first fourteen aircraft rides. Both groups eventually recognized all segments, so As are of no concern. However, the pretrained group started at a higher level,[1] and had an earlier inflection point (Px = 1.88 versus 3.73). The levels of performance at inflection were comparable (Pys = 2.09 and 2.04, respectively, for pretrained and normal groups). The cognitive pretraining thus appears to have resulted in earlier assimilation of information that both groups eventually completed.

The third example involves data from an exploratory study mentioned earlier (Isley & Spears, 1982; Isley et al., 1981). Navy pilots practiced simulated carrier landings. During early trials, percents of time in tolerance on approaches generally correlated negatively for glideslope, angle of attack (AOA), and line-up, both during the entire approach and across segments of the approach. These correlations became generally positive later in practice. Furthermore, for trials 32-48, average performance for all three components was no better than for trials 1-16. (This statement needs some qualification; for exploratory purposes, some simulated conditions were so inadequate that pilots exposed to them could not perform at all at the outset, and one pilot made no progress at all under his conditions.) However, examination of performance curves revealed an interesting fact. A subject may begin with a high percent in tolerance for one component, say AOA, and low percents for glideslope and line-up. With practice, AOA percent would drop and the others rise until they were essentially the same. Then curves for all three percents would begin to rise together. The early negative correlations were due to performance on one component deteriorating while that on one or both of the other components improved. Later positive correlations resulted from parallel improvements on all components.

Even though performance averaged across components was no better for trials 32-48 than for trials 1-16, it was evident that considerable learning had occurred. From extremely variable early performance, midway through a common level was achieved across components which was generally lower on the average than originally. Then, performance on all three components improved together,

[1] By setting X = zero in the logistic equation, estimates of performance levels prior to the first trial were obtained, 1.49 segments for the pretrained group and 0.88 for the normally trained group. Again, see Section V.

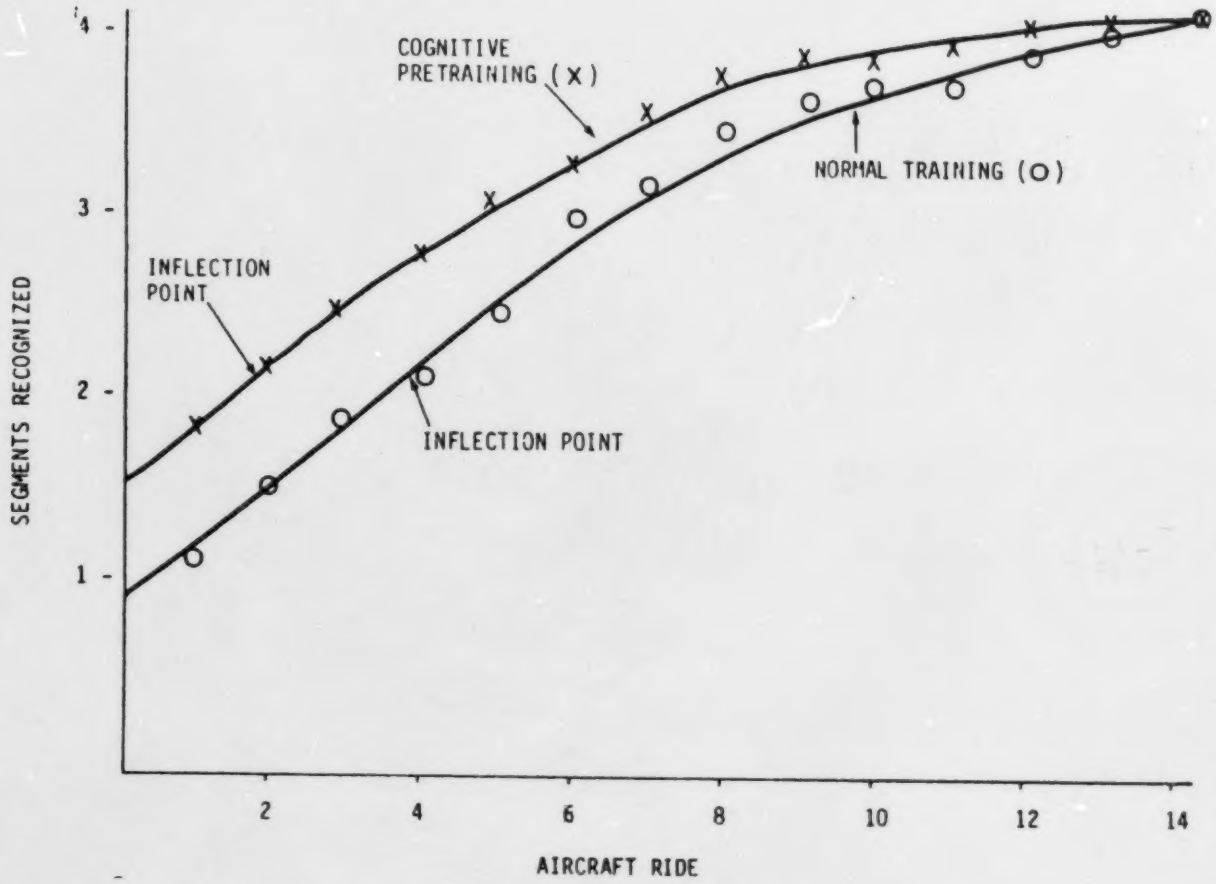


FIGURE 3. MEAN NUMBERS OF FLIGHT SEGMENTS RECOGNIZED ON SUCCESSIVE AIRCRAFT RIDES (DATA FROM SMITH ET AL., 1975).

and with relatively little variation among components. The pilots apparently started out by concentrating on one component at a time, then two, and then all three. Thus, it was easy to track the integration of all three components in the data.

Although the analyses discussed have not been employed earlier in any systematic sense, these three examples illustrate the feasibility of a systematic methodology for observing (and quantifying) skill integration.

HIERARCHICAL CHARACTERISTICS OF MOTOR SKILLS. Psychological theorists have used the conceptual tool of hierarchical organization for some time in explaining behavior. This has been especially true of theories of choice behavior as involved in schemata. Beginning with Thurstone (1927) in psychophysics and Hull (1943) in general S-R learning, hierarchical theories of choice behavior became axiomatic and mathematical. Building especially on Thurstonian foundations, other theorists (e.g., Luce, 1959, 1963) have expanded choice theory and related mathematical techniques to embrace almost any hierarchical system in which "dominance" is the essential characteristic (see Baird & Noma, 1978, for a general review). Today, theories of cognition often posit hierarchical relations for almost all aspects of information processing (see Section III).

As pointed out on several occasions in foregoing discussions, a variety of aspects of motor skills have hierarchical characteristics. These aspects range from single component clusters such as cue discriminations to situational adaptations of performance that can be ascribed to analogical hierarchical schemata. As emphasized in Section II, however, to make maximum use of hierarchical conceptions, it is necessary to focus on functional relations as the organizational factors. They can include "levels" and "dominance" without being restricted to these relations. Thus, for example, cueing sequences as well as, say, levels of cue discriminations, can be brought under the concept of hierarchy. The shifts that occur with practice, from waiting for a "new" (i.e., next) cue before responding to letting the last response cue the next one, can thereby be analyzed within many of the mathematical frameworks devised for dominance relations.

Versatility of this nature is required if the complexity of hierarchical organization is to be brought to taw analytically. Control loops and their governing schemata, for example, require not only feedback but feedforward (Summers, 1981). Which component is dominant over another may change almost continuously.

Information now available in training literature--task analyses and empirical studies of task performance--should prove very helpful in identifying at least tentative hierarchical organizations for many skills. When the organizations are viewed in terms of the analyses of cognitive and motor skills as discussed, it should be possible to address training considerations involving them. For part-task training, for example, which tasks are the best candidates? How should they be grouped? In what order should they be practiced and how far should mastery progress on each part separately? What are the requirements for whole-task integration and how should they be met? The analyses of functional relations that determine answers to these questions must consider all components of skill performance, from hierarchical structures of encoding to those of the complete skill.

EFFECTS OF INTERFERENCE. Interference effects have been mentioned in connection with a number of topics. It should be apparent that an advantage of the analysis of skills as presented here and in Section III is that the complexity of interfering processes can be appreciated. In understanding the complexity, one can address issues of training and of negative versus positive transfer specifically. It is not sufficient to know, for example, that training with a particular device results in negative or little positive transfer. In designing a training device and selecting tasks to be taught with it, one needs to know the sources of likely interference and negative transfer. Is the nature of movements the trouble? Direction of movements? Loss of initial position? Are conflicting harmonic patterns established? Do students adopt inappropriate speed-accuracy or facilitation trade-offs? Are performance standards compromised?

There is another aspect of interference which has not been mentioned thus far. In verbal learning, this aspect is subsumed under proactive and retroactive "inhibition." The significance for present purposes of these sources of interference is in the selection of tasks to be trained and patterns for practice. For example, a number of studies of motor performance have shown that constant (mean algebraic) errors in one simple movement shifts in the direction of--is assimilated into--characteristics of prior (proactive interference) and interpolated (retroactive interference) movements. (See Laabs & Simmons, 1981, for a review of these studies.) In some cases, proactive influences are effective only for very brief periods that can be measured in seconds (Craft & Hinrichs, 1971). Furthermore, interference effects can be highly specific. Distances of interpolated movements affect distances of criterion movements; end locations affect end locations (Laabs & Simmons, 1981).

The review by Laabs and Simmons left out a significant point. While they noted that the entire cue context is operative in interference, that interpolated mental activity is not particularly interfering in movements, and that the use of verbally encoded cues reduces cue conflicts, they failed to draw the inference of most value in training. Interference is inversely related to the degree of discrimination of cue-response systems. Verbal processes, including "mental activity," are not interfering to motor responses because they are supreme examples of generalized discrimination systems.

Learning of complex skills requires practice of a number of components that are mutually interfering to a novice. What the training developer needs to know is how overall detrimental effects of the interference can be reduced, and the interference itself eventually accommodated or removed.

Discriminations facilitated by deliberate verbal encoding by the learner can reduce detrimental effects (Diewart & Roy, 1978), as can achieving a reasonable level of mastery on one skill component at a time. Mastery implies discrimination of cue-response systems, and the greater the mastery of one motor skill component relative to another, the less the mutual interference (Osgood, 1953). But note the reference to "reasonable level of mastery." Oddly enough, in the learning of multiple motor skill components, the "vertical" transfer among components typically reaches a maximum prior to a high degree of mastery (Gagné & Foster, 1949). Therefore, a trade-off between positive and negative effects is in order, the precise nature of which should

vary according to interactions of components characteristic of particular skills.

EFFECTS OF FATIGUE. As with interference, the analysis of cognitive and motor skills, of their components and organization, makes possible specific statements regarding the effects of fatigue on performance. Although not especially pertinent to present purposes, a brief review of these effects will round out these analyses. More important, the effects themselves can serve as indicators of inefficient training regimens. If a training session or practice on a particular task is too long or intense, resulting fatigue can be detrimental to learning. As explained below, unwanted alterations occur in performance. If these alterations are practiced, they are likely to be learned. At best, the undesirable aspects would interfere with the learning desired, and at worst replace it. A good rule to follow is to let training progress to the point of noticeable fatigue only when the specific purpose for the training is to accommodate the fatigue.

Holding (1981) gave a succinct summary of fatigue effects on skills. First, there is a deterioration in personal standards for performance. The deterioration may result in lax monitoring (e.g., greater tolerance of deviant readings on instruments) or in acceptance of less than adequate performance outcomes. Second, there are lapses in attention, if not overall, at least for cues and actions related to peripheral aspects of the task. In other words, what are perceived as essential aspects may be attended, but not those privately considered non-essential. Third, performers become more easily distracted, with consequent loss of acuity needed for monitoring performance. Fourth, there is a tendency to "cut corners" during performance. Shingledecker and Holding (1974) reported that subjects who had first become fatigued on a complex monitoring task tested fewer components on a following fault isolation task. They were willing to accept the risk of not identifying the faulty component (facilitation trade-off with a new perspective). A similar reduction in effort was found by Barth, Holding, and Stamford (1976) in subjects cranking an ergometer after running on a treadmill until tired.

These last three effects of fatigue can all be considered variations of the first one, deterioration of standards for performance. (They can involve different mechanisms and indicators, however.) Other effects relate to the breakdown of overall skill organization. During fatigue there is greater variability in responses, especially in timing. In some cases responses that would be correct at some points are simply made at the wrong time. In others, response integration deteriorates. We might hypothesize that movement harmonics are disrupted, probably due either to inconsistent or delayed reaction times. This seems to have been the case with the fatigued runners studied by Bates, Osternig, and James (1977). Foot descent became slower, forward swing of the legs more rapid, while other components did not change in duration. Holding (1981) also noted that integrated skills tend to "separate" into individual components during fatigue.

Finally, there can be a deterioration in judgment. For example, Brown, Tickner, and Simmonds (1970) found that during the last three hours of a twelve-hour driving stint, drivers attempted 50 percent more "risky" overtaking maneuvers than during the first three hours. Brown et al.'s data are at odds with those of Potts (cited by Brown et al.) who found that "near

accidents" decreased with time on task. However, ignoring the difference in criteria, there can be significance in the apparent contradiction. Potts' subjects were long-distance truck drivers and apparently Brown et al.'s were not. (The latter subjects were identified only by ranges of age and driving experience.) Either through safety training programs or experience, truck drivers would be more likely to learn to accommodate fatigue, to anticipate its effects and correct for them. If this is the explanation, perhaps it can suggest ways to train for fatigue accommodation for long or tedious (or boring) tasks.

# SECTION V

## MANIFESTATIONS OF TRANSFER IN TRAINING

The concept and mechanisms of transfer (and interference) have been treated at length in earlier discussions. Section II attempted to set the stage for later discussions by establishing (1) that transfer is a process of learning as well as a product; (2) that "common element" conceptions of transfer are truly as inapplicable to training as critics of this approach--including some who adopt it in practice--would have us believe; and (3) that transfer can be reasonably understood only if its locus is seen as mediational processes.

Section III expanded all three points at length. In fact, there is nothing discussed in Section III that does not involve transfer. All short-term processes draw on long-term memory (LTM)--past experience--for attentional processes involved in signal detection, for encoding of inputs and their elaboration, and for retrieval of information. The executive processes are ipso facto discriminative, generalizing transfer systems. As analogical schemata, they determine how a task is "recognized" (defined) in terms of situations, how task performance is comprehended and planned, and how ensuing actions are monitored, regulated, and evaluated.

Section IV extended the discussion to cover motor skills. As in Section III, the roles of transfer (and interference) are seen to be complex. Facilitation or disruption can occur at numerous points during processing; one component of a skill may show effects of training the opposite of that for another component.

But training devices, especially part-task and low-fidelity devices, raise a further transfer issue. Trainees who learn skills using them must be able to practice the skills with equipment, and in situations, that differ qualitatively from those for training. It is not practical for training developers or the designers of training equipment to anticipate the myriad possible transfer effects that can occur during, and as a result of, device training. It is enough to recognize generally what might happen, at what stage in processing, and why, and to provide for contingencies as best they can. A later extension of the present effort is to develop definite guides for these purposes. Nevertheless, there will usually be enough uncertainty to call for empirical indicators of the nature of transfer of device training to operational equipment and situations.

The purpose of this section is to present four such empirical indicators. All are parameters of performance curves that can be readily quantified. Three of the performance parameters, beginning level, asymptotic level, and rate of learning, have been used in the experimental psychology of learning for some time. Also, their value for measuring transfer has been recognized (cf. Deese, 1958, p. 216; Woodworth & Schlosberg, 1954, p. 736-738). The fourth parameter, an inflection point, is a derivative of rate. To the writer's knowledge, it has not been used previously to measure either learning or transfer.

Each of these parameters is described in the discussions that follow, along with training factors that can affect them. Their measurement is illustrated using data from studies of training. The examples are drawn from pilot training because these data were readily available. The points made apply to all training, however, for the conceptualizations and quantitative formulations originated in hundreds of empirical studies of learning of all kinds. While the focus is on transfer, the use of control groups shows that the measures are generally applicable to both original learning and transferred learning.

There is also a brief discussion of the significance of each parameter for studies of transfer in applied settings. To simplify discussions, a convention is adopted to distinguish between the learning that is to be transferred and the learning or performance that is presumed to be affected by the transfer. Following the usual paradigm for studies of transfer, "Task 1" will designate the skills practiced by a learner, the effects of which on later performance or learning are at issue. "Task 2" will denote the skills whose later performance or learning is the basis for inferring Task 1 transfer effects. Task 2 would be the first task, of course, for a control group whose skill acquisition is to be used as a basis for assessing Task 1 transfer.

For example, an experimental (transfer) group could practice instrument flight skills in a simulator (Task 1), and later be tested for proficiency in these skills in an aircraft (Task 2). A control group might practice only in the aircraft (Task 2). Transfer of simulator learning to aircraft performance could then be assessed by comparing Task 2 performance by the two groups. To the extent that the experimental group was superior to the control group on various aspects of, or at particular points during, Task 2 practice, positive Task 1 transfer will be said to have occurred. Conversely, to the extent the opposite is true, the inferior aspects of performance of the experimental group will be termed negative transfer. Zero transfer will mean that Task 1 practice had no effect either way on Task 2.

## GENERAL COMMENTS REGARDING CURVE FITTING

Measures of the four parameters require the fitting of curves to learning and transfer data, and discussions of the parameters will require fewer digressions if seven points regarding curve fitting, equations used, and interpretation of results are clarified. First, curve fitting assumes that learning and transfer are lawful processes. If this assumption cannot be justified, all efforts to study variables affecting these processes are in vain. A hundred years of research have shown unequivocally that learning and transfer are highly lawful, and highly predictable when extraneous influences on the data are controlled. It is also well known that a number of equations can describe the observed regularities. That is, they can relate observed dependent ($Y$) values to functions of independent ($X$) variables within the limits of experimental control. Furthermore, the choice of equations can be based completely on empirical considerations. No assumptions need be made regarding the nature of learning and transfer, and no theory is involved unless the researcher chooses to use theory.

Second, curve fitting permits the use of all data to derive measures for each of the four parameters. In contrast, consider customary methods of

measuring rate of learning and Task 2 beginning level. Rate may be estimated, for example, by comparing achievement on first and last trials, and beginning level by measuring achievement on the first one or two trials. However, results for individual trials are quite unreliable--notoriously so for first trials--so a valid method that uses all data for each measure is necessarily superior.

The third point follows directly from the second. Individual trials in applied training research are often subject to a variety of uncontrollable extraneous influences such as weather variations during aircraft practice, irregular spacing of trials, use of substitute instructors, etc. Curve fitting cannot remove the need for experimental control, but by deriving measures from the data as a whole, fluctuations due to uncontrollable influences on individual trials are cancelled out for each parameter to the extent they are random across groups. Curve fitting also permits reasonable estimates of what would have occurred on a given trial if the uncontrollable influences had not been present. In other words, if curve fitting had no other advantages, it would still be desirable for research in applied settings where rigorous experimental control is not possible.

Fourth, all curves discussed in the following sections were fit using the least squares method. That is, constants for the equations represented by the various curves were derived so as to minimize the overall squared errors in predicting observed measures of learning or performance from the independent variables.

Fifth, to avoid having to interpret "goodness of fit" of the curves to data by relating mean squared errors to variances of the dependent ($Y$) measures, the closeness with which each empirical curve fits its data is reported as the product moment correlation $r$ between actual $Y$ values and those predicted by the curve. The $r$s tend to be very high, as they should be if the data are not too irregular and the equations to fit them are properly chosen.

The sixth point concerns the possible statistical significance of differences that occur in the examples. Data were not available in sufficient detail to test for significance, but this is no problem for present purposes. The intent is to illustrate how parameters can be measured and their value for interpreting learning and transfer data. Therefore, illustrative interpretations do not necessarily apply to the individual studies discussed. Rather, true effects of the sorts discussed are common in learning research, and it is the illustration of effects that is of concern, not the particular research findings.

The seventh point concerns the designation of variables and constants in equations. The only experimental variables of concern are the measures of learning or performance, represented by $Y$, and the independent variable, $X$, which can represent measures such as number of trials, hours of practice, number of reinforcements, time since practice (for studies of retention), etc. Measures of parameters of interest such as $B$ (beginning level), $A$ (asymptotic level), $R$ (rate of learning), and $P$ (inflection point) are represented in upper case as shown. Lower case constants $h$, $g$, and $k$ are used in generic forms of equations unless and until they are defined as $B$, $A$, etc.

BEGINNING LEVEL

Beginning level B is defined as the level of performance before any practice on the task to be learned. This definition holds for either Task 1 or Task 2 learning. B may well be zero, but such an assumption should not be made without ample justification. As has been stressed, even novices enter a training situation with a background of experience that can help learning the task at hand. In some cases, of course, prior experience can interfere with new learning. Such interference can result in a low or even negative B.

B cannot generally be measured without fitting curves to data. An example will illustrate why. The data represented in Figure 4 are from a report by Prophet and Boyd (1962). An aircraft group practiced a set of cockpit procedural tasks in an A0-1 aircraft. The 2-C-9 and mock-up groups practiced the same procedures in a 2-C-9 procedures trainer and a photographic mock-up trainer, respectively. The latter groups then continued practice on the same procedures in the aircraft. The data points in the figure represent mean percent errors on aircraft transfer trials 1-5 for the 2-C-9 and mock-up groups, and on original learning trials 1-6 for the aircraft group. There were 10 subjects in each group.

The earliest data available for the complete trial 1 in the aircraft cannot be assumed to represent B. Each trial required from 15 to 30 minutes per subject. Unless the procedures involved were completely independent of each other--a most unlikely possibility--the cumulative experience during trial 1 will result in the acquisition of new skill components, or the sharpening of previously learned ones, that will affect performance later in the same trial. It follows that errors in performance observed for trial 1 as a whole are determined jointly by a beginning level B and rate of learning during trial 1.

The curves in Figure 4 project each set of data back to the Y axis. Bs are the points at which the curves intercept the Y axis, i.e., "achievement" on the zeroth trial $X_0$. Each curve represents the equation

$$Y = h + ge^{-kX}$$

where Y is a measure of percent errors, X is the aircraft trial, h, g, and k are constants to be determined by fitting the general equation to the data, and e is the well known mathematical constant.

Table 1 shows these constants together with percent errors on the first trial in the aircraft, derived Bs, and rs between actual and predicted Ys. Bs were derived by letting $X = 0$, in which case $e^{-kX} = e^0 = 1$, yielding $B = Y_0 = h + g$. Comparisons of first-trial errors and Bs show how greatly first-trial measures may be contaminated by rate of learning. The 2-C-9 and mock-up groups are not as similar at the outset as they appear at the end of the first trial (10.3 percent errors versus 10.4 percent, respectively, as opposed to 14.9 percent and 19.2 percent for $X = 0$). Furthermore by comparing Bs for the aircraft and two transfer groups, the transfer from preaircraft (Task 1) training is seen to be greater than comparisons of first trial performance of aircraft and transfer groups indicate.

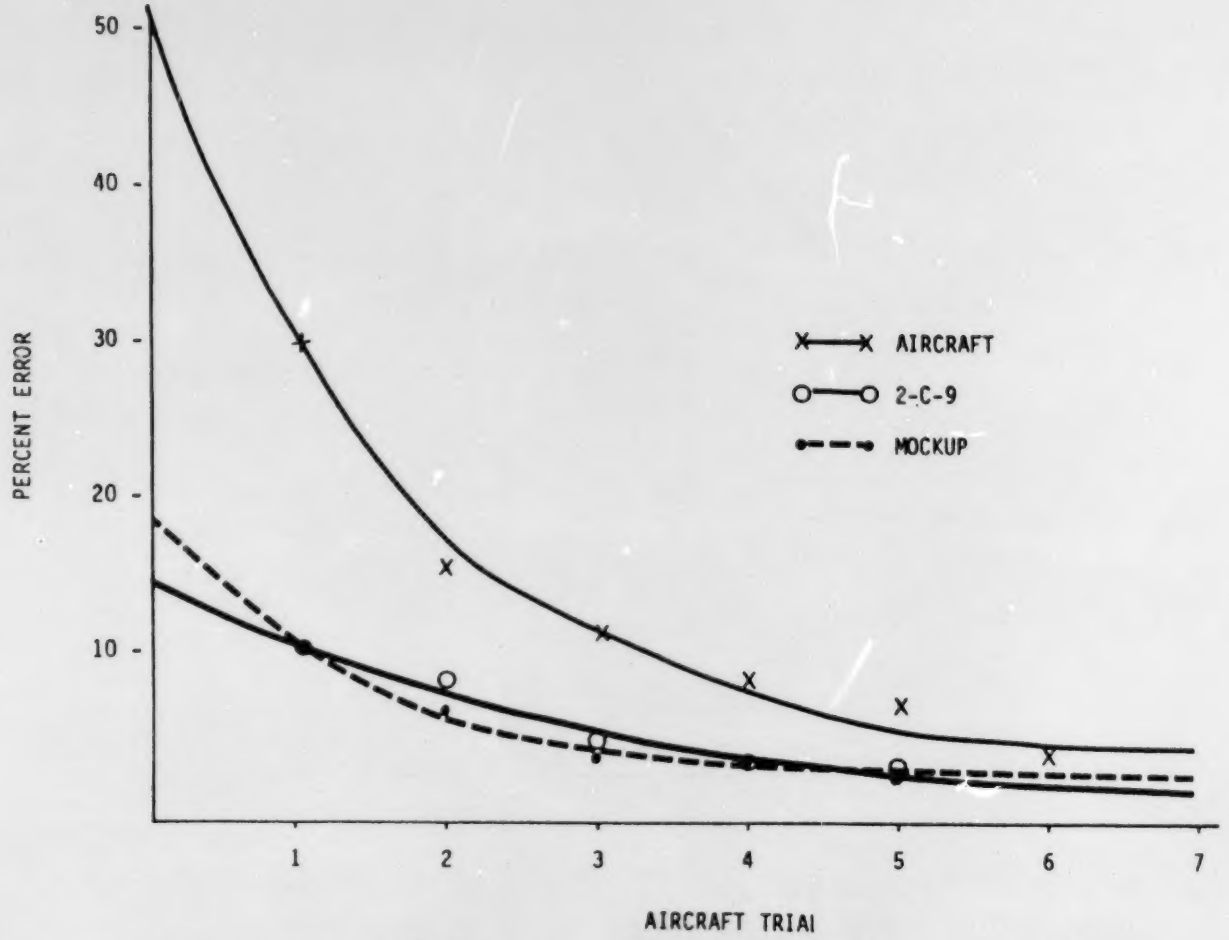


FIGURE 4. MEAN PERCENT ERROR FOR THREE TRAINING GROUPS ON SUCCESSIVE AIRCRAFT TRIALS (DATA FROM PROPHET & BOYD, 1962).

TABLE 1. AIRCRAFT FIRST-TRIAL ERRORS AND VALUES DERIVED THROUGH CURVE FITTING

| Group | Percent errors on first trial | B | r | Constants h | g | k |
|---|---|---|---|---|---|---|
| Aircraft | 29.5 | 50.3 | .994 | 4.2 | 46.1 | .147 |
| 2-C-9 | 10.3 | 14.9 | .997 | 1.0 | 13.9 | .359 |
| Mock-up | 10.4 | 19.2 | .971 | 2.8 | 16.4 | .273 |

Note: Original data from Prophet and Boyd (1962). Constants shown have been rounded to too few digits to compute the tabled r exactly.

Much more could be said about these data if the implications of constants h and k were explored. However, the purpose here is to illustrate a measure of B that is independent of rate of learning, and to lay a foundation for discussing it later in relation to the other parameters of learning and transfer.

UNITS FOR B. B can be stated either in units of Y or of X. In the former case, B represents performance level prior to practice, as has been stressed thus far. It is just as easy, however, and for some purposes more appropriate, to express B in X units, i.e., the number of practice trials, amount of training time, etc., that, because of experience, subjects had "completed" on an equivalent basis prior to Task 2 practice. In the Prophet and Boyd data the beginning performance level of the 2-C-9 group of 14.9 percent errors was equivalent to 2.4 aircraft trials, while the mock-up group's B of 19.2 percent was equivalent to 1.8 aircraft trials. In either case there could be a substantial savings in aircraft costs for a sizeable group of trainees.

These trial equivalents were determined by setting the equation for the control group equivalent to B for each of the other two groups and solving for X. Another technique is to represent each X in the equation as $(X_i + X_o)$ where $X_i$ is the trial number and $X_o$ the B level in X units which is to be determined during the fitting of the curve. Estimating $X_o$ by the latter method does not require a control group, and the $X_o$ obtained is not dependent on the performance of a control group.

These alternative units for B can be valuable for studies of transfer in which comparisons are to be made of costs of alternative Task 1 training procedures or conditions. For example, the amount of Task 2 training effort saved can be measured directly in terms of Task 2 dependent variables (level of beginning performance) or independent variables (equivalent aircraft trials), whichever is preferred.

TASK 2 BEGINNING LEVEL AND TRANSFER OF TRAINING. As explained earlier, B is an estimate of what learners can do on Task 2 before they even try. It is not what they might understand, for example, that will help them adapt quickly to Task 2 requirements after they begin practice. This careful specification of the nature of B is important, for as will soon become apparent, how one evaluates facets of a training program, and decides what changes to make to improve it, will usually require distinguishing between B and other parameters of transfer, especially rate of learning.

Persons who insist that simulator fidelity is required for transferable learning apparently have B in mind as the primary measure of transfer. If a learner can do the same things, in the same way, experiencing the same cues and feedback, in a training device that he can using operational equipment, then what he learns in the device is ipso facto measured by B. Grant for the present that stimulus and response fidelity is one basis for transfer, and that it affects Task 2 B level. It remains to broaden this conception so that B can be seen as a more inclusive measure.

Specifically, to the extent that a learner can, through mediational processes and especially imagery, construct a psychological realism that equates subjective Task 1 experience to actual Task 2 conditions and actions, Task 2 B level will be affected regardless of objective stimulus and response similarity of the two tasks. The study by Prophet and Boyd (1962) just discussed showed this clearly. In a more general vein, Wheaton, Rose, Fingerman, Korotkin, and Holding (1976) concluded after an extensive review of research literature on learning and transfer that "imaginative," i.e., completely cognitive, practice could be substituted on a one-to-one basis for some practice trials even in motor skill learning. The only requirements are that the learner be able already to perform the motor acts involved in Task 2 but that cannot actually be done during Task 1 (e.g., positioning switches in a photographic mock-up), and that the learner's past experience be sufficient for symbolic cues and actions to have precise meaning. Under these conditions, B measures can reflect transferable Task 1 learning of any sort, including some aspects of purely cognitive learning acquired during academic instruction. Note, however, that some aspects of fruitful cognitive learning during Task 1 cannot improve B, and may even depress it. The positive effects become manifest later in training. This will soon be apparent.

B can also be affected in a negative manner, especially when sets established during Task 1 training restrict adaptability to performance requirements, or when motor coordinations are learned in a device whose dynamics are different from those of the equipment that is to be used operationally. In such cases, Task 1 interference (proactive inhibition) can occur. As illustrated in a later section, Task 2 rate of learning may well render such negative B transfer inconsequential. Nevertheless, for diagnostic efforts directed at training program improvements, it would be well to know whether B does in fact reveal a negative Task 1 effect. Typical measures such as percent transfer may show that transfer is substantial overall, but isolating a negative aspect makes possible specific instructional or equipment changes that can result in even better overall transfer.

ASYMPTOTIC LEVEL

The asymptotic level of performance A is a mathematical conception that one may have qualms about at first glance. As will be demonstrated, however, A can be a very revealing measure of learning and transfer. The reason for possible qualms will be discussed first, and then valuable uses of A which such reservations do not affect will be explained.

A is defined as the limit for Y (achievement) as X (the independent variable) increases indefinitely. In the equation used earlier to fit the Prophet and Boyd data,

$$Y = h + ge^{-kX},$$

one conceives of X approaching infinity. As it does so, $e^{-kX} \longrightarrow 0$ for a positive k, so $Y \longrightarrow h$, the asymptote for this equation.

In practice, X rarely becomes even sizable, much less infinite. Furthermore, A can be a limit of performance only for conditions as they exist. Not only will conditions for skill performance change with time, but changes within the learner while undergoing training can affect ultimate possible achievement levels. The well known "plateaus" in learning curves illustrate this phenomenon. A subject may improve during practice up to a point at which progress appears to stop, only to accelerate again as the learner makes new adaptations to the conditions for performance or new integrations of the skills involved. Each plateau represents a temporary A. Bryan and Harter (cited in Woodworth & Schlosberg, 1954) found this to be true in one of the earliest experimental studies of skill learning, and it is illustrated in data from Smith, Waters, and Edwards (1975) shown in Figure 5. In the latter study, an experimental group received intensive cognitive pretraining for a T-37 overhead traffic pattern, while a control group received only the training "normally" given undergraduate pilot trainees. Both groups were tested during 14 subsequent aircraft rides to determine the number of flight segments and landmarks they could recognize. Figure 5 shows the mean number of landmarks recognized by each group on each of the 14 rides. The plateaus are too regular to ignore. Indeed, to sort out all the effects of the cognitive pretraining, we need measures of all four parameters--B, A, rate of learning R, and inflection point P. A is the present concern, and the purpose of introducing the Smith et al. data at this point is to illustrate that plateaus do occur in research on training, to point to their significance, and to emphasize that A relates to them.

Their significance was summarized succinctly in McGeoch and Irion's (1952) influential text on human learning: "The conditions under which such variations as these [plateaus] take place, as well as the conditions which determine the rate and limits of improvement, form the proper subject matter for a large portion of this book" (p. 29). In passing, it is pointed out that patterns of plateaus such as these are typical when (1) successive integrations of elements are necessary to progress in a skill, and/or (2) cognitive processes must be interfaced with the perceptual and motor realities of skill requirements. Thus, the points at which plateaus occur, and the levels of achievement they represent, can be indicative of important processes and stages of training in ways that reflect training effectiveness and efficiency.

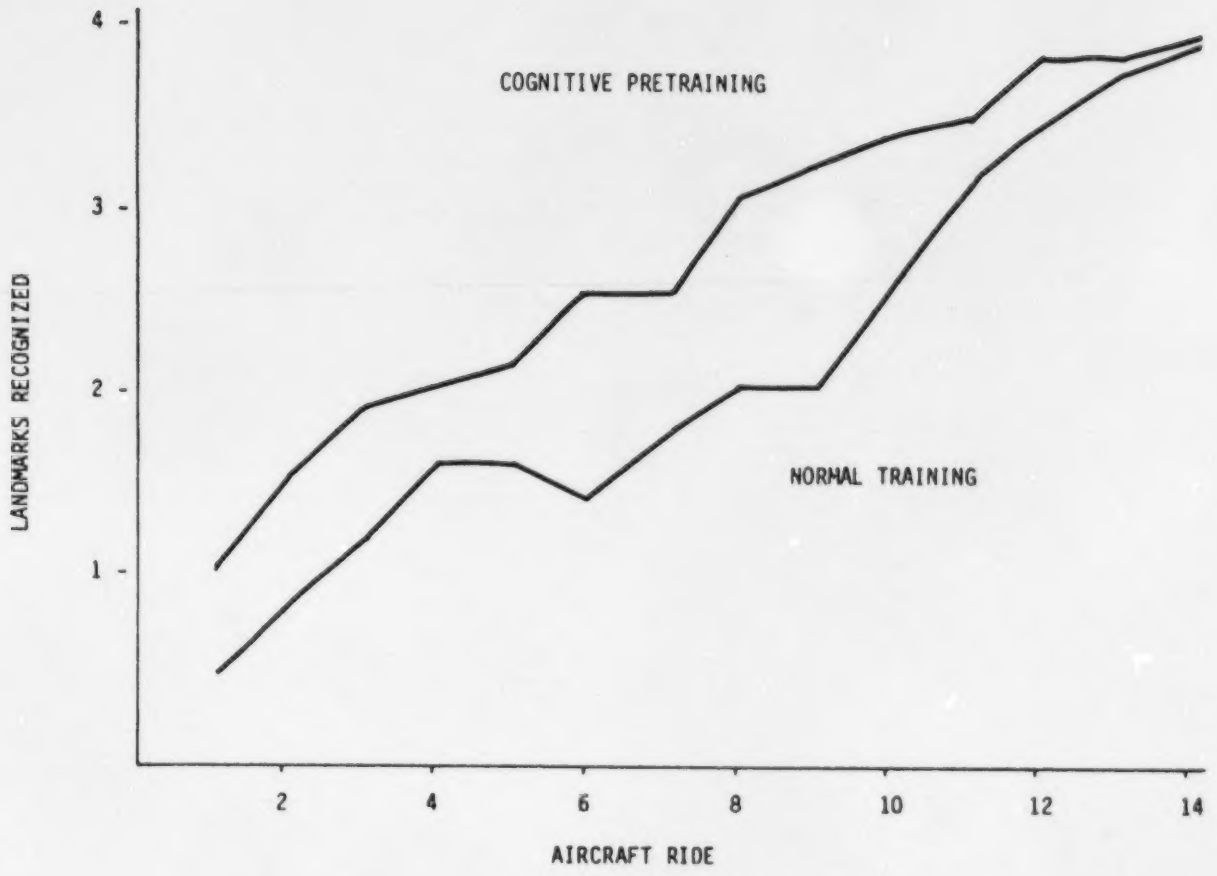


FIGURE 5. MEAN NUMBER OF LANDMARKS RECOGNIZED ON EACH OF 14 AIRCRAFT RIDES (DATA FROM SMITH ET AL., 1975).

Computed for each segment, A can yield a stable estimate of the performance level at which a plateau occurs.

To lay a foundation for a discussion of A as an indicator of transfer, two other uses of A in training research will be illustrated. One concerns its predictive value in training, and the other its potential for deriving implications of data that usually are not apparent.

The data in Table 2, taken from Prophet (1972), represent percent errors in performance during each of the first five days of aircraft practice following simulator training. Groups are identified by checkride grades assigned on approximately the 28th day of helicopter trials, except for 16 subjects who washed out either before the checkride or on the checkride. Each group of data was fit using the equation

$$Y = \frac{AX}{X + k}$$

where Y is the cumulative percent error, X the day number, A the asymptote, and k a constant related to the rate of learning (see below). B = 0 for all groups.[1] Table 3 shows As, rank order of As, and rs between actual and predicted Ys for the various groups. Note that three curves were fit for each group, one using only days 1-3, one using days 1-4, and one using all five days. For the four groups at the bottom of Table 3, the ranks of As correlate perfectly with ranks of checkride grades assigned some time later after an additional 20 or more aircraft trials. The rank correlations are less than perfect when the groups are broken down into smaller grade ranges, but they are still high: .93 when all five or four days are used, and .86 for three days.

Of course, in this example (but not generally) the correlations are just as high if cumulative errors are used rather than As. However, as will be apparent when these data are considered further under rate of learning, As provide potentially valuable predictive measures in combinations that are impossible to obtain without them.

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[1] When cumulative data represent Y values, it is customary to assume B = 0 because, to use the present example, no aircraft errors could cumulate prior to aircraft trials. This argument is arbitrary in that a decision could have been made to project errors back in time to preaircraft performance. However, either of two conditions, both of which are satisfied here, justify ignoring B so long as it is not of interest. First, can the data be fit closely if B is assumed to be zero? The rs in Table 3 show that the answer to this question is yes. Second, if Bs had been estimated for the groups, would the Bs differ? The data in descending form (i.e., not cumulative) shown in Table 2 were fit to an appropriate function, and Bs were found to be essentially the same across groups. Therefore, the cumulative values may be viewed as having a constant B subtracted from each Y, which would not affect the form of the equation or the goodness of fit.

TABLE 2. PERCENT ERROR FOR SEVEN MANEUVERS BY DAY OF TRAINING AND CHECKRIDE GRADE

| Group | N | Training Day 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Precheckride W/O[a] | 13 | 63 | 62 | 60 | 57 | 57 |
| Checkride W/O | 3 | 60 | 51 | 58 | 45 | 55 |
| 70-74 | 6 | 66 | 54 | 48 | 34 | 35 |
| 75-79 | 10 | 42 | 40 | 36 | 30 | 40 |
| 80-84 | 8 | 50 | 35 | 34 | 32 | 23 |
| 85-89 | 7 | 49 | 40 | 29 | 28 | 22 |
| 90-94 | 9 | 45 | 35 | 29 | 22 | 24 |
| All W/O | 16 | 62.4 | 59.9 | 59.6 | 54.8 | 56.6 |
| 70-79 | 16 | 51.0 | 45.2 | 40.5 | 31.5 | 38.1 |
| 80-89 | 15 | 49.5 | 37.3 | 31.7 | 30.1 | 22.5 |
| 90-94 | 9 | 45 | 35 | 29 | 22 | 24 |

Note: From Prophet (1972).

[a]W/O identifies groups that washed out.

TABLE 3. ASYMPTOTIC LEVEL A FOR CUMULATIVE ERRORS BY CHECKRIDE GRADE AND NUMBER OF DAYS USED TO FIT EQUATION

| Group | Days used to fit equation 1 - 3 r | A | Rank | 1 - 4 r | A | Rank | 1 - 5 r | A | Rank |
|---|---|---|---|---|---|---|---|---|---|
| Precheckride W/O | 1.000 | 6334 | 7 | 1.000 | 5296 | 7 | 1.000 | 5031 | 7 |
| Checkride W/O | .999 | 1264 | 5 | .999 | 1384 | 6 | .999 | 1606 | 6 |
| 70-74 | 1.000 | 713 | 4 | 1.000 | 678 | 4 | 1.000 | 676 | 4 |
| 75-79 | 1.000 | 1356 | 6 | 1.000 | 1101 | 5 | 1.000 | 1202 | 5 |
| 80-84 | .999 | 346 | 2 | .999 | 398 | 2 | .999 | 421 | 2 |
| 85-89 | 1.000 | 422 | 3 | 1.000 | 424 | 3 | 1.000 | 425 | 3 |
| 90-94 | 1.000 | 372 | 1 | 1.000 | 366 | 1 | 1.000 | 378 | 1 |
| All W/O | 1.000 | 3811 | 4 | 1.000 | 3629 | 4 | 1.000 | 3739 | 4 |
| 70-79 | 1.000 | 852 | 3 | 1.000 | 780 | 3 | 1.000 | 809 | 3 |
| 80-89 | 1.000 | 378 | 2 | 1.000 | 410 | 2 | 1.000 | 423 | 2 |
| 90-94 | 1.000 | 372 | 1 | 1.000 | 366 | 1 | 1.000 | 378 | 1 |

Note: As (cumulative errors by group, not percents), and rs between actual and predicted Ys, for curves fit to data in Table 2.

Some data from Martin and Waag (1978), discussed in Section IV, illustrate the value of A for pinpointing possible skill integrations during training that may not be readily apparent. Recall that two groups of subjects flew training sorties, 10 by each subject, in a simulator. One group experienced platform motion and the other did not. The performance of each group was rated on various tasks by instructor pilots (IPs) during five of the trials. The data points in Figure 1 (Section IV) represent mean ratings for each group on an overhead pattern. The points are connected with straight lines to provide a contrast with Figure 2, also in Section IV, where solid curves are shown representing the logistic equation,

$$Y = \frac{h}{1 + ge^{-kx}} .$$

Bearing in mind that the IPs used a 12-point rating scale, and that the highest mean rating for either group was 6.56, what do the curves in Figure 2 suggest that is not apparent in Figure 1? In brief, it appears that the patterns of data may well say more about the effects of motion than the data points per se can reveal. The curve for the motion group is still rising on the fifth evaluated trial, while that for the no-motion group is not. Recall that in the previous example, As derived from error counts were good predictors of subjective checkride grades after more than 20 additional aircraft trials. A for the present motion group was 8.97, but only 6.36 for the no-motion group. The indications are that the motion group, due to continued integration of motion cues, could have improved well beyond the plateau reached by the no-motion group. (This conclusion is supported further by an analysis of the inflection points in the curves. See later discussion.)

ASYMPTOTIC LEVEL AND TRANSFER OF TRAINING. The relation of A to transfer of training is quite different from that of B and transfer. B measures the extent to which Task 1 learning is immediately manifest in Task 2 performance. Intuitively, one might say that B represents the portion of performance learned during Task 1 that is functionally congruent to Task 2 requirements without a need for adaptations to Task 2 conditions. On the other hand, A builds on B, but in doing so represents effects of Task 1 learning during Task 2 that cannot be manifest at the outset because it is not immediately congruent to Task 2 requirements.

One example of delayed effects of Task 1 learning is their influence on successive integrations of skill components during Task 2. Both cognitive and perceptual-motor aspects of Task 1 learning are likely to be involved. Procedural tasks, for example, become less and less rote in nature as skill components are organized into patterns and hierarchies--Greeno's (1977) "comprehension" criterion discussed in Section III. Task performance becomes more stable as a result, and is more likely to be retained (Prophet, 1976; Schendel, Shields, & Katz, 1978). Recognizing that such skills, depending on their complexity, may follow a sequential pattern of plateaus as shown earlier in Figure 5, A represents a dependent variable for both Task 1 and Task 2 learning that can identify the point at which a given stage of integration is completed, and the level of achievement at that stage. Given a particular level of achievement, how early in training it is approximated can be readily

determined by noting the X value at which Y approximates a given percent of A. Or, given plateaus for two or more groups, A can indicate the level of, say, skill integration that has been achieved by each.

Another value for A was pointed out by Woodworth and Schlosberg (1954, p. 665-666). The difference between A and beginning level B is a basis for viewing what is or could be accomplished during training. By fitting a curve to the data (which they recommended), answers can be obtained to questions such as, How much of the possible learning was achieved in the first X trials? At what point during practice was a given proportion of the possible learning achieved? Answers to these questions could be important for defining optimal levels of Task 1 practice prior to attempting Task 2, especially for part-task devices; or if optimal levels are already known, for identifying achievement levels short of "mastery" to be used in comparing training methods.

RATE OF LEARNING

Rate of learning R is widely recognized as an important measure of efficiency of training. Decisions regarding the allocation of time, personnel, and material resources to training depend heavily on how rapidly trainees learn.

Because rate of learning has been a, if not the, primary criterion for decisions regarding training allocations and practices, most researchers in training studies attempt to measure it, and existing measures are quite useful for a number of purposes. However, they are often crude, and they frequently confound R with other variables, especially beginning level, in ways that prevent measures of R from providing the information they could. Furthermore, it is likely that uses of R in evaluations of training more often than not are governed by the nature of R measures conveniently available rather than by what would be desirable for the purposes of the evaluations. The fact that cost analysts bemoan the inadequacy of measures of rates of learning is a case in point (cf., Orlansky & String, 1977).

Rate of learning is defined as the change in achievement per unit of change in the independent variable. Stated symbolically,

$$R = \frac{\Delta Y}{\Delta X}$$

where the deltas indicate "change in" Y or X. To explore the meaning of R, however, and to relate it to learning processes, it is necessary to examine $\Delta Y / \Delta X$ in relation to the equations used to describe learning data. The task is much simpler if $\Delta X$ is considered to approach zero as a limit, for then the differential calculus can be used. Using the standard notation, $dY/dX$ will be substituted for $\Delta Y / \Delta X$ as $\Delta X \longrightarrow 0$.

The dependence of R on the nature of the equation involved can be seen readily by comparing two functions frequently used to describe learning data. (They are also two of the oldest.) One, the exponential growth equation (also termed the monomolecular equation in chemistry), is

$$Y = A(1 - e^{-kX})$$

where A and e have their usual meanings. If this equation, after suitable adjustments, is differentiated with respect to X, the result is

$$\frac{dY}{dX} = k(A - Y) = R.$$

This differential equation has a straightforward intuitive interpretation. A is the asymptote, the maximum to be learned, so (A - Y) is the amount not yet learned, and k is a proportionality constant.[1] Thus, the rate of learning R (=dY/dX) on, say, a particular trial is a constant proportion of what has not yet been, but can be, learned.

The second illustrative equation was used earlier, viz.,

$$Y = \frac{h}{1 + ge^{-kX}}.$$

For its differential form, the so-called autocatalytic monomolecular (AM) equation,[2]

$$\frac{dY}{dX} = kY(A - Y),$$

will be used because it permits direct comparison with the one immediately preceding.

While for the first equation, R was, so to speak, a constant proportion of the learning yet to go, in the second equation R is the same except that the proportion is multiplied by the amount already learned. In other words, learning catalyzes itself; it "snowballs." The more the learning, the faster learning occurs. In view of vertical transfer processes that can occur during training, it is especially important to be able to identify their effects. More on this below.

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[1] In most discussions of learning curves, k is referred to as a measure of rate of learning, which it is provided As are the same, and the same equation is used for all groups. Otherwise, k is not linearly transformable to dy/dx = R.

[2] Apparently, it is not generally recognized that this equation is one form of the more general equation. Compare Lewis' (1960) statement that the AM equation has had no theoretical basis in psychology (p. 465), and Estes' (1963) criticism of its uses, with Estes' (1950) earlier employing it in the logistic form given above for theoretical purposes. If k in the logistic equation is transformed to k' = k/A, the AM differential equation holds for the logistic equation.

An example using data from Brictson and Burger (1976) will illustrate the need for measuring R in a manner that it does not become confounded with B. One group of subjects first practiced night carrier landing training in a trainer, Device 2F103 (NCLT group). A second group practiced only in the A7E aircraft. The data points in Figure 6 represent mean ratings by a Landing Signal Officer of landing performance of each group on the first eight attempts in the A7E.

The data are highly irregular, due almost surely to variations in flight conditions and to instabilities in performance that characterize early learning of carrier landings (Isley et al., 1982). Order is brought to the data, however, and clear patterns emerge when curves are fit to them as in Figure 7.

Each curve in Figure 7 represents three radically different equations, the exponential growth function, the logistic function, and the Gompertz function, a double exponential equation (see Lewis, 1960). The reason for using three equations, even though the fits are essentially identical, will become apparent.

The first thing to notice is that the transfer (NCLT) group was superior overall, even though its B was clearly below that for the control group. The overall superiority was due to a rate of learning that overcame the original handicap before the 4th trial, and continued to a higher A level. The implication is that the device training resulted in negative transfer as far as B was concerned, but at the same time laid a foundation for unusually rapid progress once the transfer group transitioned to the aircraft. A training program or device designer might well want answers to two questions: What is the source of the negative transfer as regards B? What were the characteristics of the device training that led to rapid skill acquisition in the aircraft?

There is not enough information available in the research report to answer either question, but two points are pertinent. First, had there not been a basis for differentiating R from B, the questions would not have even been asked. One might suspect from Figure 6 that two different types of manifestations of transfer were evident, but the possibility did not demand attention until curves were fit to the data as in Figure 7. Now that the difference is obvious, one can narrow down possibilities for program improvements to factors that led to a negative B effect. (See earlier discussion this section of Beginning Level and Transfer of Training, and Intersensory Transfer in Section IV.)

Childs, Lau, and Spears (1982) provided an excellent example of the complexity of transfer with respect to B, A, and R. Half of a group of pilots transitioning from a single-engine aircraft to a multi-engine aircraft had prior practice using a training device of very low fidelity. The other half of the group practiced only in the multi-engine aircraft. There was a substantial negative transfer effect on B that dissipated completely after the first aircraft day. In fact, the negative effects held only for maneuvers practiced on the first aircraft day. Maneuvers that were practiced in the aircraft for the first time after the first aircraft day showed no negative B effect at all. Furthermore, there was a positive transfer effect on A as

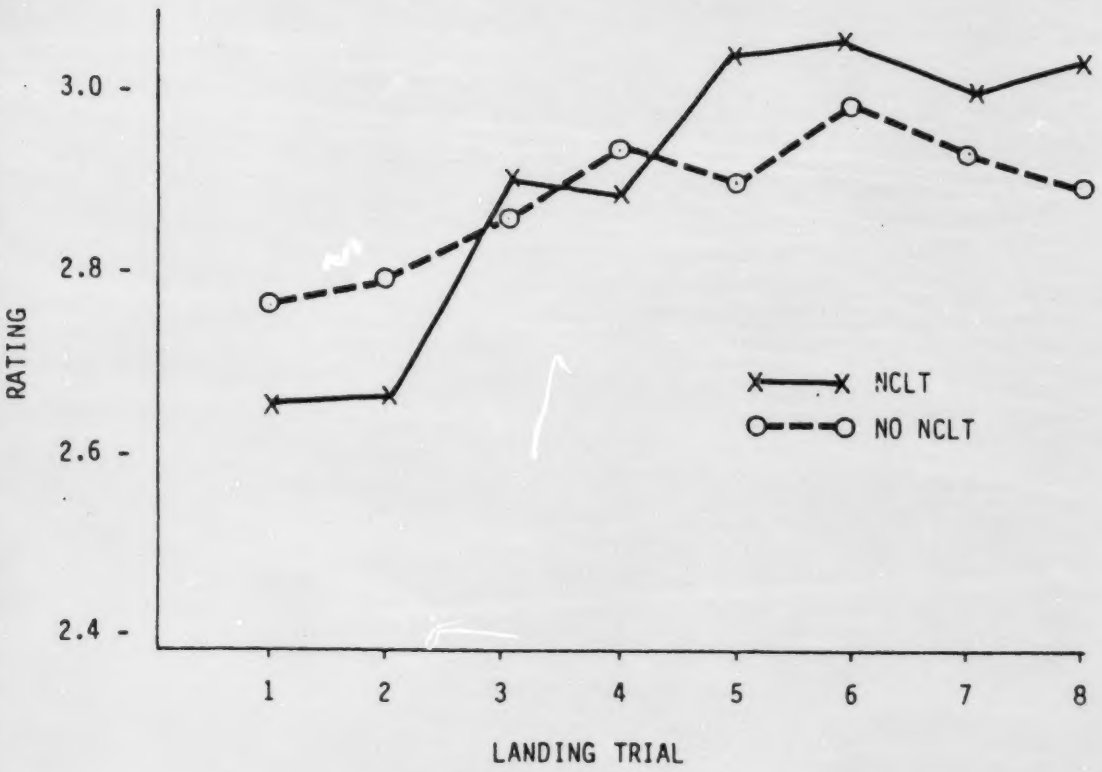


FIGURE 6. MEAN RATINGS BY LANDING SIGNAL OFFICER FOR GROUPS WITH AND WITHOUT PRIOR NCLT TRAINING (DATA FROM BRICTSON & BURGER, 1976).

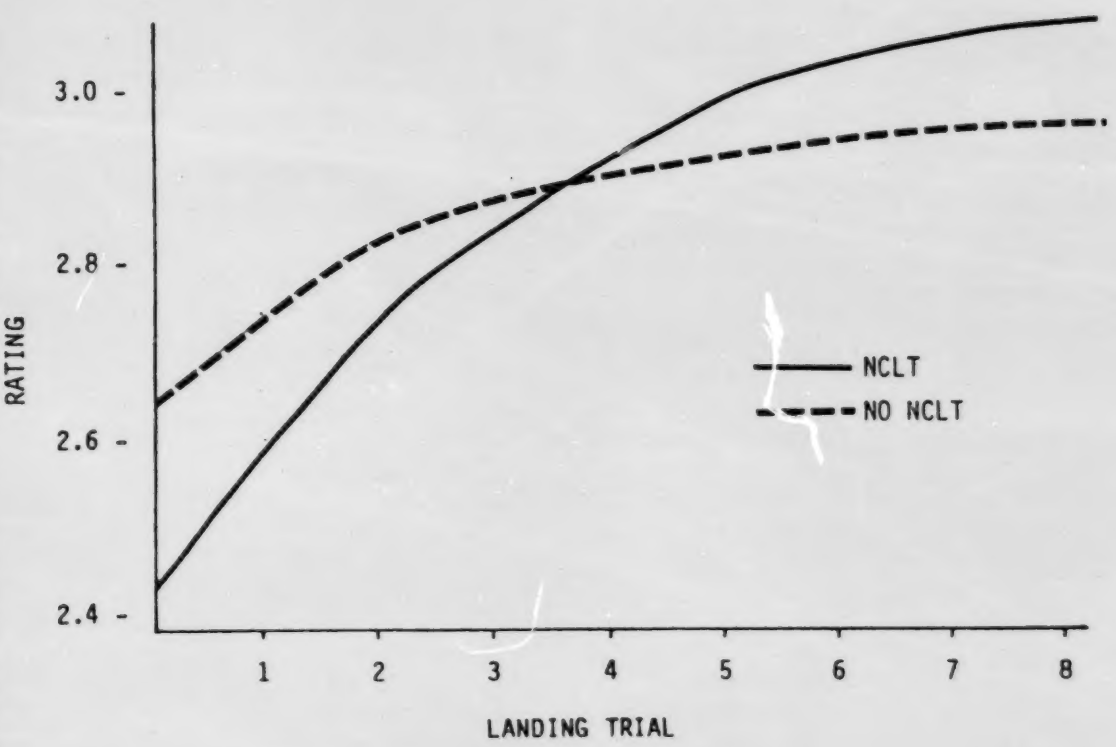


FIGURE 7. CURVES FITTED TO DATA POINTS IN FIGURE 6.

represented by performance on the final checkride following aircraft training. It was also evident that early aircraft practice on one maneuver in particular generalized to performance while learning other maneuvers (vertical transfer), resulting in a higher rate of learning R. Childs et al. explained that the low device fidelity forced cognitive learning during practice with it, thus enhancing A due to better cognitive organization. However, B was depressed because the original cognitive representation of tasks was not adequate for immediate implementation in the aircraft. With practice, however, the perceptual-motor interface was quickly achieved. (Their data were not adequate to explain why early training on one particular maneuver had a substantial vertical transfer effect on R, though the effect appeared due to the precise discriminations needed for the maneuver. See discussion of structural characteristics of movements in Section IV, specifically Simon's [1956] finding that amount of transfer depends on the number and type of discriminations involved.)

The second point concerns the analytic possibilities of R for the Brictson-Burger data. Recall the differential forms discussed earlier,

$$R = k(A - Y)$$

for the exponential growth function, and

$$R = kY(A - Y)$$

for the autocatalytic function. The first equation implies that learning simply accumulates, while the second implies that learning not only accumulates, but utilizes previous learning (vertical transfer) to speed up the process. In other words, learning becomes a tool for subsequent learning. Therefore, the fact that these two equations fit the data equally well--so nearly equivalently that one curve represents both equations--is of considerable significance to one concerned with the design of training programs. That is, with respect to the second alternative above, an equation that assumes learning only accumulates fits the data as well as one that assumes the accumulation is enhanced by successive levels of achievement. Therefore, whatever NCLT training contributed, it did not facilitate using successive stages of learning as a tool for subsequent progress. Had one or both patterns of data yielded a sigmoid (S-shaped) curve, implying a snowballing effect, only the autocatalytic equation could have fit the data. (Sigmoid effects are suggested by the data points, but apparently they are due to chance variations.) Had a sigmoid curve been obtained only for the NCLT group, for example, the inference would have been that NCLT training resulted in a "learning to learn" phenomenon while aircraft training did not. This kind of analytic distinction reveals what has been, as opposed to what might be, accomplished in Task 1 training.

Another use for R is illustrated by the predictive value of related ks for the data from Prophet (1972) that were discussed earlier. Table 4 shows ks and their ranks for the various groups defined by final checkride grades. Data are given separately for fits of the equation using days 1-3, 1-4, and 1-5. Recall that the equation used was

$$Y = \frac{AX}{X + k}$$

so the smaller the k, the faster the progress toward A.

TABLE 4. RATE CONSTANT k FOR CUMULATIVE ERRORS BY CHECKRIDE GRADE AND NUMBER OF DAYS USED TO FIT EQUATION

| Group | Days used to fit equation: 1 - 3 k | 1 - 3 Rank | 1 - 4 k | 1 - 4 Rank | 1 - 5 k | 1 - 5 Rank |
|---|---|---|---|---|---|---|
| Precheckride W/O | 99.51 | 7 | 82.99 | 7 | 78.78 | 7 |
| Checkride W/O | 20.14 | 5 | 22.16 | 5 | 25.94 | 5 |
| 70-74 | 9.81 | 4 | 9.28 | 4 | 9.24 | 4 |
| 75-79 | 31.26 | 6 | 25.17 | 6 | 27.59 | 6 |
| 80-84 | 5.95 | 1 | 7.01 | 1 | 7.50 | 2 |
| 85-89 | 7.59 | 3 | 7.65 | 3 | 7.66 | 3 |
| 90-94 | 7.26 | 2 | 7.15 | 2 | 7.41 | 1 |
| All W/O | 60.09 | 4 | 57.15 | 4 | 58.97 | 4 |
| 70-79 | 15.72 | 3 | 14.28 | 3 | 14.85 | 3 |
| 80-89 | 6.65 | 1 | 7.31 | 2 | 7.59 | 2 |
| 90-94 | 7.26 | 2 | 7.15 | 1 | 7.41 | 1 |

Note: Equations were fit to data from Prophet (1972); compare with Tables 2 and 3.

The rank correlations between grade group and k are perfect for 4 and 5 trial-days when the larger groupings are used. When broken down into seven groups, the correlations are .79 for days 1-3 and 1-4, and .86 for days 1-5. That the predictive information from ks does not duplicate that from A is evident in the less than perfect correlations between ks in Table 4 and As in Table 2. (A and k must correlate highly with each other for these data, however, because each correlates so highly with a third variable.)

It was mentioned when the Prophet data were discussed under asymptotic level of learning that a regularity existed that could be observed only through curve fitting or comparable techniques. This regularity is revealed in two different ways. In Table 5, percent errors for each group on the 28th day were projected from curves fit only for days 1-3, 1-4, and 1-5. Y values were cumulative percent errors, so the projections were made by entering X = 28, and X = 27, in each equation and taking the difference.[1] The general trend shows that the differences predicted from equations for three, four, and

[1]This approach was used rather than a differential equation for dY/dX because the change in X of one day is not near enough to zero for $\Delta Y/\Delta X$ to approximate dY/dX.

five days increase slightly in stability as final checkride grades are higher, but that predictions vary very little for a given group regardless of the number of days used. This suggests that performance observed early in training can reveal what will eventually be accomplished.

TABLE 5. PROJECTED PERCENT ERRORS ON DAY 28 BY CHECKRIDE GRADE AND NUMBER OF DAYS USED TO FIT EQUATION

| | Days used to fit equation | | | | | |
|---|---|---|---|---|---|---|
| | 1 - 3 | | 1 - 4 | | 1 - 5 | |
| Group | Percent errors | Rank | Percent errors | Rank | Percent errors | Rank |
| Precheckride W/O | 39 | 7 | 36 | 7 | 35 | 7 |
| Checkride W/O | 11 | 5 | 12 | 6 | 15 | 6 |
| 70-74 | 5 | 4 | 4 | 4 | 4 | 4 |
| 75-79 | 13 | 6 | 10 | 5 | 10 | 5 |
| 80-84 | 1 | 1 | 2 | 2 | 2 | 1.5 |
| 85-89 | 3 | 3 | 2 | 2 | 3 | 3 |
| 90-94 | 2 | 2 | 2 | 2 | 2 | 1.5 |
| All W/O | 30 | 4 | 29 | 4 | 30 | 4 |
| 70-79 | 7 | 3 | 7 | 3 | 7 | 3 |
| 80-89 | 3 | 2 | 2 | 1.5 | 2 | 1.5 |
| 90-94 | 2 | 1 | 2 | 1.5 | 2 | 1.5 |

Note: Equations were fit to data from Prophet (1972); compare with Tables 2, 3, and 4.

A question remains, however. The values shown in Table 5 are independent of levels of error occurrences. That is, differences between performance on days 27 and 28, predicted from three, four, or five days of observations, are quite small, but what about the stability of predictions on day 28 alone? The answer is obtained by measuring the variabilities of cumulative errors predicted from equations for three, four, and five days. For the 90-94 checkride grade group, the standard deviation was 2.86, while the standard deviations were 11.3 for the 80-89 group, 11.9 for 70-79, and 7.4 for all washouts. The 90-94 group is significantly less variable than the other three whose standard deviations do not differ significantly. (But note that all standard deviations are very small compared to the magnitude of cumulative errors for Day 28.) It is apparent that, for the groups whose checkride grades fell within the 90-94 range, a curve using only data from the first three days is essentially the same curve as one using five days, but that the curves diverge slightly for lower checkride grades.

Variability in performance has been recognized previously as an important indicator of level of skill integration, and it was demonstrated to apply in one study of simulator training for carrier landings (Isley and Spears, 1982; Isley et al., 1982).

RATE OF LEARNING AND TRANSFER OF TRAINING. The discussion of the data from Brictson and Burger (1976) revealed an important relation between R and transfer. In that case, Task 1 experience, although resulting in some negative transfer at the outset, provided an impetus for Task 2 learning that more than overcame the original deficit. Being able to measure such an impetus, or the lack of it, is necessary for analytic evaluations of training programs--what trainees achieved, how they achieved--as well as research on transfer of training.

A broader picture of the value of R can be obtained by an understanding of the mechanisms of transfer. A few brief comments will illustrate the value of the analyses in Sections III and IV.

First, any behavior can be viewed as a complex of components, some of which are facilitating, some interfering or disruptive, and some neither. In skills requiring psychomotor coordinations, it is important to guide the learner at the outset to practice facilitative components and avoid those that produce disruptive interference. Training devices offer excellent opportunities for training in this manner. Guidance and feedback can be specific to actions, and tasks or parts of tasks can be learned in hierarchical sequences that maximize rate of progress (Caro et al., 1981). In other words, training programs can be designed to optimize learning and instructional processes rather than to conform to the exigencies of operational equipment. Rate of progress during Task 1 learning thus is a criterion for training efficiency, and during Task 2 learning, for confirming training effectiveness.

There is another aspect of transfer which has not been studied formally as a transfer phenomenon per se to any great extent in military training. As demonstrated in Section III, it should be, and R together with A would have to be the primary variables of interest. Specifically, all cognitive training to support motor skills necessarily depends on transfer. With a few notable exceptions, cognitive training in military programs has not been evaluated within a transfer paradigm. Pencil and paper tests are used instead. Yet, one of the earliest studies of transfer by Judd published in 1908 (cited by Woodworth & Schlosberg, 1954) showed how purely "academic" training can transfer to performance of a motor skill. The study is worth reviewing because it has clear implications for using R during Task 2 to evaluate cognitive training. (Judd's study was repeated by Hendrickson and Schroeder [1941] with similar results.) One group of fifth- and sixth-grade boys were taught principles of light refraction (Task 1). They and a comparable control group then practiced hitting a target submerged twelve inches under water (Task 2). The groups performed equally well. Next, the target was raised so that it was only four inches under water, and the subjects tried again. The transfer group was clearly superior the second time. Knowing about refraction did not help until the knowledge had been interfaced with an action. Transfer of the conceptual knowledge, once interfaced with psychomotor skills acquired in the first Task 2 effort, was evident.

Hundreds of learning studies could be cited to support the point: Cognitive training can provide a framework for adapting motor actions to the requirements of the situation, but the framework cannot be assessed until after the motor elements are acquired and related to the framework. Thus, B cannot measure many contributions of cognitive training to skill performance. It is

restricted to those components which do not require the learning of an interface. R can measure such contributions directly. If the use of cognitive training during skill performance, as indicated by R, is evaluated according to the nature of the cognitive training, manner of instruction, etc., significant improvements can be possible in cognitive instruction. (Also, because comprehension provides a broad scope of possible uses of skills, as well as a basis for self-guidance and self-correction in skill performance, good cognitive foundations can be expected to result in high asymptotic levels of performance.)

The exceptions alluded to earlier regarding the use of transfer paradigms in applied training studies to evaluate cognitive training typically involved what is termed either "cognitive pretraining" or "dynamic observation." Both types of studies have merit, but as implied in Section III, they have hardly scratched the surface compared to what could be done. (A cognitive pretraining study is examined in the next subsection.)

The versatility of R for research on transfer is illustrated by its value for deducing mathematically measures of transfer commonly in use. The various ratios for estimating percent of transfer (Gagné, Foster, & Crowley, 1948; Murdock, 1957; Ellis, 1965) and transfer efficiency (Povenmire & Roscoe, 1971; Roscoe, 1971, 1972) all incorporate a rate concept. The advantage of R is that, being derived from all data, it provides reliability not possible for measures based on only pairs of observations. Furthermore, if Task 2 B levels, A levels, or Rs obtained[1] for different amounts of Task 1 practice (as in Roscoe's incremental transfer paradigm) are fit to equations, Rs derived for the incremental functions can measure rate of change of Bs, As, and even Rs as a function of amount of Task 1 practice. Incremental transfer can thus be analyzed into separate types of components, with a reliable measure of the rate of change.

INFLECTION POINT

The inflection point P of a learning curve is that point at which a positive acceleration changes to negative, or vice versa. In a sigmoid (S-shaped) curve, for example, it is the point at which the rate of learning stops increasing and starts slowing down, even though progress continues on the whole. Mathematically, it is the X value for which the second differential of the equation for the curve equals zero.

P apparently has not been used as a parameter for studying learning and transfer. From a logical standpoint, it could be a valuable measure. The sudden bursts of progress that occur when skill integration occurs, when skill elements "fall into place," or when cognitive understanding becomes interfaced with skill performance, will produce a curve like that in the first part of Figure 8 where rate of progress is increasing. As shown, the inflection occurs at $X = 8.79$, for beyond this point rate of progress becomes slower and slower.

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[1] Rs can be unreliable when As or Bs are not known a priori, but there is a strategy for getting around the problem. See Estes (1950).

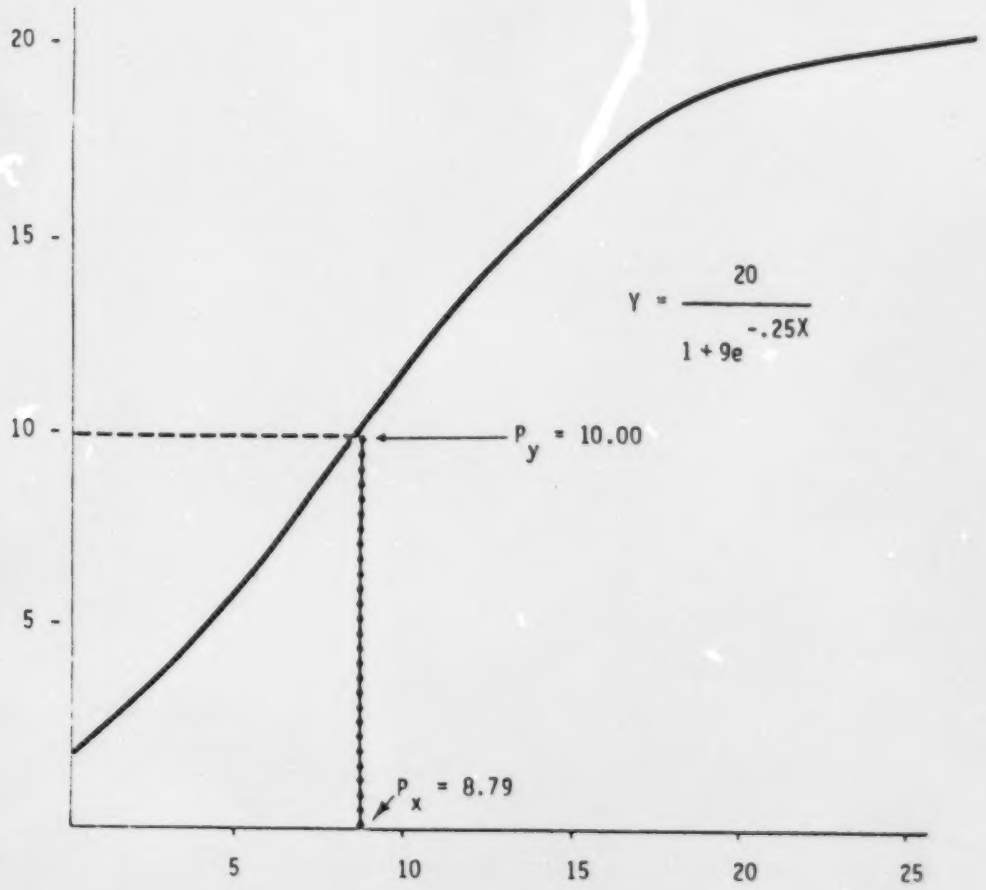


FIGURE 8. ILLUSTRATION OF A LOGISTIC CURVE WITH INFLECTION POINT IN UNITS OF X AND Y.

As shown in the figure, P can be measured in units of either X or Y. The formal definition of P just given is in units of X, i.e., $P_X$. The level of achievement corresponding to a given $P_X$ can be determined by entering $P_X$ into the equation for the curve and solving for Y. This latter value will be referred to as $P_Y$.

A study discussed earlier illustrates how $P_X$ and $P_Y$ can aid in interpreting learning and transfer data. Recall in Section IV that the data from Martin and Waag (1978) appeared at first to favor a no-simulator-motion group (see Figure 1 in Section IV). However, curves fit to these data as shown in Figure 2, also in Section IV, projected an A for the motion group substantially higher than the A projected for the no-motion group. Ps for these curves support the validity of these projections. For the no-motion group, $P_X$ = 0.90 and $P_Y$ = 3.18; for motion, $P_X$ = 2.78 and $P_Y$ = 4.48. It is evident that the period of positive acceleration was briefer for the no-motion group, and that rate of progress began to decelerate at a lower achievement level. Considering that acceleration and deceleration patterns can reflect underlying integrations of skill components, it is reasonable to conclude (tentatively) that (1) motion cues in addition to those shared with the no-motion group comprised a larger set of stimuli to be integrated; (2) that the integration required more practice; (3) that when integrated, the more complex set of stimuli permitted a higher level of performance; and (4) building on the greater amount of information in the more complex cue patterns, skill achievement can be expected to continue to a higher A level than would be the case for the less complex (no motion) set of cues.

Some data from Smith et al. (1975) illustrate a different pattern of Ps, one in which only $P_X$ differed. As explained earlier, they gave one group of student pilots intensive cognitive pretraining to aid in recognizing flight segments and landmarks, while a control group had only "normal" instruction. Recognition of landmarks during later aircraft rides showed a pattern of plateaus as discussed earlier under asymptotic levels of learning. The pattern of recognition of flight segments revealed an instance where P can provide useful information. Figure 3 in Section IV shows logistic curves fit to the mean number of flight segments recognized for each of the first 14 rides, and Table 6 gives the As, Bs, ks, and Ps for each of the two groups of data. The fits of the equations are quite good as indicated by the rs in the table.

TABLE 6. CONSTANTS FOR CURVES FOR NUMBERS OF LANDMARKS RECOGNIZED

| Group | r | A | B | k | $P_X$ | $P_Y$ |
|---|---|---|---|---|---|---|
| Pretrained | .998 | 4.17 | 1.49 | .311 | 1.88 | 2.09 |
| Normally trained | .999 | 4.09 | .88 | .347 | 3.73 | 2.04 |

Note: Data from Smith et al. (1975).

The $P_X$ show that the control group probably did not have the full advantage of autocatalytic learning, of building learning on learning (see earlier discussion of R), until just before the fourth aircraft trial, while the pretrained group reached this point just prior to the second aircraft trial.

The $P_X$s alone might indicate that the pretraining group "topped out" too soon; but in view of their superior B levels, and the fact that $P_X$s are essentially the same for both groups, it appears that the cognitive framework for recognizing flight segments did not affect what would be integrated as in the preceding example, but it did permit a degree of integration of pertinent cues during Task 1 and/or very early in Task 2 that the control group did not achieve until later. Note how quantifying several parameters facilitates interpretation of each one in terms of what occurs during training.

INFLECTION POINT AND TRANSFER OF TRAINING. The examples just discussed reveal an important relation between P and transfer. By pinpointing when learning curves change from positive to negative acceleration, it can indicate the point during practice where certain integrative processes are completed. Stated in units of Y (achievement level), P can be related to the proficiency level of transferred skills. Such indications can be of value when the Task 1 learning at issue is of a cognitive nature. However, as illustrated in the analyses of Martin and Waag's data, the value of P is not likely to be limited to purely cognitive Task 1 learning. Many motor skills involve noncognitive integrations, and develop in a sigmoid manner regardless of cognitive components. P might just as well indicate, say, when a pattern of part-task practice results in a superior integration of skill components early in, or prior to, Task 2 practice.

# SECTION VI

# VALUE OF ANALYSES FOR TRAINING AND TRAINING RESEARCH

This section summarizes the value of the foregoing analyses for the design of training programs and related equipment. It also suggests three research topics, arising from the analyses, that would help the value to be realized.

## ASSESSMENT OF SKILL ANALYSES FOR TRAINING

Sections III and IV reveal an optimism regarding the potential value of modern conceptions of cognitive and motor skills for guiding training design. While these conceptions are often criticized for slighting instruction, as they have been on occasion in this report, the fact remains that there is a difference between a theory of learning (or performance) and a technology of instruction. By far, most of the investigators whose work and ideas have been cited in this report were concerned with theories of performance, but with the implication that the theories set forth the foundations of learning. That is, they specified the nature of what is to be learned. At the same time, their methodologies, in isolating individual processes, for example, resulted in extensive analyses of roles of processes and conditions that can facilitate or interfere with performance and learning. This last statement is true even of research in motor performance, an area where learning has been especially ignored in recent work.

The development of a training technology, to a great extent, involves nothing more than insightful extensions to instruction of what is known and is continually being clarified regarding the nature of skills. Suggestions as to what is involved appeared often in preceding sections--an operational language for manipulating variables (Section II); equating processes of skill acquisition to those of problem solving (Section III); the integration of tasks comprising skills (Section IV); etc. Thus, the richness of modern conceptions of skill performance has much to offer.

At the same time, the concerns of a few cognitive theorists for an instructional technology, dating to the 1960s, are now supplemented by a growing emphasis on instruction. (Concept formation has, of course, been of interest for decades.) Bruner (1966) was a relatively early major figure, as was Gagne (1962, 1965, 1968) whose impact on military training is evident in ISD. Glaser's emphasis on instruction, ranging from programmed learning to modern cognitive theory, has also been evident since the early 1960s (Glaser, 1962, 1965) and continues to the present (Glaser, 1976, 1982). But increasingly, there have been reports of analyses and experiments by a number of theorists that bear on the adaptation of cognitive theory to instruction. Compare, for example, the nature and scope of articles in Cognitive Skills and Their Acquisition (Anderson, 1981) and the reviews by Resnick (1981) and Wittrock and Lumsdaine (1977).

This concern with instruction apparently is not characteristic of investigators of motor skills (Newell, 1981). Part of the lack is almost surely due to the lag, relative to cognitive skills, of theoretical

development of the processes involved in motor performance, and to the fact that academic researchers of motor processes--except for a few in departments of physical education--do not have a training context for their research. Even so, as explained in Section IV, some conceptions of motor skills (e.g., closed-loop or cybernetic theory, Adams, 1971; Smith & Smith, 1966) lead naturally to a training technology. Furthermore, as one ponders the logically necessary roles of schemata in motor performance, it is evident that what holds for the training of cognitive schemata applies in some fashion to teaching motor skills.

The conclusion is that a training technology, derived from present knowledge, can be available. Although far from complete, the technology that could be derived promises much beyond the oversimplified, yet significant pioneering work of a Thorndike. The question is how to proceed in the development of the training technology. The next subsection addresses this question through illustrative examples of research and development efforts that are sorely needed. Deliberately omitted as an example is an extrapolation of earlier analyses of skills to the design and use of part-task and low-fidelity training devices. This is a logical enterprise that should be pursued in a subsequent study. The research suggested below would add empirical substance to the logic.

## ILLUSTRATIVE RESEARCH PROJECTS

There is no way to conceive of the number of research projects that could develop from systematic applications of modern theories of skills to problems in skill training. Every processing unit, cognitive or motor, can be a candidate for applied research on any skill, component task, and mode of training. Research of this nature will eventually be required. However, the duplication of effort from skill to skill can be drastically reduced by adopting a strategy that answers as many fundamental questions as possible on a general, and generalizable, basis. For example, the nature of stimulus and response similarity as related to device fidelity requires a cognitive analysis for adequate understanding of what is involved. For each skill, one could go through the mapping procedure suggested in Section II, incorporating the processes detailed in Section III. But there is a logically prior question that, when answered, could render comprehensive skill-by-skill, device-by-device, analyses of cognitive similarity completely unnecessary. What is the nature of the cognitive representation of the skill, of its analogical correspondence to situations for its performance? It is desirable to know the analogical correspondence in any case, so cognitive similarity, being one aspect of correspondence, would be analyzed only to the extent necessary to understand correspondence.

The strategy would not be to develop a comprehensive methodology for analyzing cognitive similarity, for such a methodology would probably go into issues of no particular importance. On the other hand, a methodology for determining correspondence would encompass any procedures for analyzing cognitive similarity that might be needed, and in the process define useful goals for those procedures, thereby limiting them to what is needed for training. In a broad sense, this strategy is implicit in the illustrative research topics discussed below. The topics concern (1) procedures for learning analyses; (2) examination of the nature and process of skill integration; and (3) providing for interpretable manifestations of transfer.

PROCEDURES FOR LEARNING ANALYSES. It was stated in Section I that learning analyses are needed to guide the design of training programs and related equipment. Discussions in Sections II-IV reveal just how far learning analyses should go beyond ordinary task analyses, and employment of ISD procedures, for deriving training regimens. Task analyses are needed to identify elements of correct skill performance. However, in and of themselves, they do not lead systematically to a training regimen because they make no allowance for the development of the host of separate executive, short-term, and long-term processes that are the essence of skill learning and performance. Furthermore, ISD procedures recognize these processes only intuitively in that ISD focuses primarily on training inputs and response outputs, ignoring what happens in the processing of inputs to produce outputs.

The research suggested here would develop a prototypical methodology for comprehensive learning analyses that would guide the training analyst in applying what we know about discrimination and generalization learning to the processes involved in skill learning and performance. There would be three main facets to learning analyses. First, task analyses would identify skill components and conditions and criteria for performance. Procedures for task analyses are, of course, already well developed. Nevertheless, a precaution often cited should be observed: What one gets from a task analysis depends, whether consciously or unconsciously, on the purpose the analyst has in mind at the time. To be useful in learning analysis, the task analysis should clearly pursue the goal of identifying task elements, performance conditions, etc., that can have representation in the cognitive-motor processing that underlies skill performance. For example, task analyses do not ordinarily designate completion of certain subtasks as subgoals to be achieved. One cannot exploit what is known regarding the roles of subgoals in the cognitive organization of skills unless they are recognized as subgoals, including their interrelations with other tasks in the overall comprehension of skills.

A second facet of learning analyses is what was termed cognitive analyses in Section III. A cognitive analysis would focus on all the executive and long-term processes discussed in that section, together with short-term processes that comprise the training interface. Especially important would be the cognitive differences between experts and novices in a given skill, for the differences would identify what must be learned. Similarly, when applicable, there should be a comparable analysis of purely motor processes as detailed in Section IV. (One may or may not wish to call these latter processes "cognitive." It does not matter what they are called, however, so long as they are recognized as essential elements in information processing.) Again, task analyses as ordinarily conceived can often be inadequate, even as task analyses. For example, when skill elements must have harmonic interrelations, it is not sufficient to identify only the cues, responses, and performance criteria for task elements. At least the broad nature of the coordinations required should be specified so as to guide the analyst in identifying patterns of harmonic consonance during information processing.

The third aspect of learning analyses is applying principles of learning and behavior to the development of the cognitive-motor processing of information. With the knowledge derived from cognitive task analyses, the targets for training would thus become the entire matrix of information processing, not just output variables.

Because the intent is to establish a prototypical methodology for learning analyses, at least two types of skills should be considered, one dealing primarily with procedures and one requiring problem solving as in troubleshooting. If feasible, a third type of skill that involves coordinated motor performance should also be included. For each skill, the three aspects of learning analysis just discussed would be pursued, more or less in order.

The approach to the cognitive-motor analyses needs special comment. At the outset, the organizational structures of the cognitive-motor systems characteristic of experts in the skills should be determined. Several kinds of information are of interest, depending on the skill: (1) patterns of cognitive representations of tasks comprising a skill, including higher order equivalence of hierarchical structures that vary in details from one expert to another; (2) relations among task requirements, perceived goals, and the cognitive representations; (3) relations of cognitive representations to characteristics of various situations for performing the skills; (4) similar relations with other skills that accompany or must otherwise be coordinated with the skill at issue; (5) patterns of encoding (attentional factors in perception, rehearsal strategies, etc.) of situational inputs and monitoring of actions; (6) subgoals and checkpoints that are established and the contingencies for actions related to each; (7) the backlog of information in long-term memory--its content, organization, and "rules" for actions; (8) patterns of task integration, focusing on timing and intra- and intertask coordinations; (9) variations in timing and coordinations together with factors that lead to them. (The list is not exhaustive.)

Considerable idiosyncratic organization of these structures can be expected, even in experts. However, this need not be as formidable a difficulty as it may seem. For example, it was explained in Section IV that speed-accuracy and facilitation trade-offs are subject to habitual processing patterns that vary with individuals. Thus, harmonic patterns in motor performance can also be expected to be idiosyncratic, as was observed by Westra[1] for pilots practicing simulated aircraft carrier landings. Further, as discussed in Section IV, Isley and Spears (1982) and Isley et al. (1982) found that patterns of attending subtasks during simulated landings varied from pilot to pilot, and for a single pilot from one trial or trial segment to another. Although the data are not as clear-cut, there is also evidence that the same thing happens during field carrier landing practice (Isley et al., 1982) in which pilots fly the carrier landing approach and touch down as if they were landing on a carrier.

But regardless of idiosyncratic patterns in harmonics and attention, the fact remains that there should be commonality in patterns of integrated performance. Recall from Section IV the need to establish an overall harmonic pattern [illegible] which separate movement harmonics are consonant. It follows that while experts may differ in harmonic timing per se, their performance should reveal similar patterns of task elements that are in harmonic consonance. These patterns would identify task components for which consonance is to be developed. Such information can go a long way toward defining device characteristics. Dynamic fidelity, for example, is needed in a device to the

[1]Westra, D. Personal communication, November, 1981.

extent harmonic patterns of separate movements are to be integrated in a manner that will not produce interference when the trainee practices with actual equipment. This is not to say that the timing of movements must be the same for the device and actual equipment. Because compression of actions, i.e., performing a task in a shorter time period (see Section IV) is apparently no problem, the requirement is that devices foster the same relative timing in the two situations.

The next step is to complete similar cognitive-motor analyses for novices in the skills. Where do trainees start with respect to each of the kinds of capabilities of experts? For many skills, novices may have almost none of the capabilities except long-term habits and understandings of a generalized nature. Even so, it would be well to analyze further the expert's long-term knowledge (item 7 above) to determine what it has in common with that of novices. Thereby, one can identify what novices begin with that can be built upon, what needs expansion, etc. For some kinds of long-term knowledge, it will be evident that cognitive pretraining is desirable (in the broad sense, not just what currently goes by this name in applied training). For other kinds, it will be apparent that concurrent or prior perceptual and motor practice are desirable to provide experiential meaning for cue-response discriminations and concepts. The nature of and criteria for prior and concurrent perceptual-motor practice should also be fairly clear.

Next, well established principles of discriminative learning should guide the design of practice so that novices' skill structures, such as they are, progress to the cognitive-motor organizations characteristic of experts. As discussed in Section II and illustrated throughout Sections III-IV, the discriminative learning should target generalized discriminative systems (schemata), so varied practice should be introduced accordingly. Feedback during training should vary in kind and occasion, sometimes process by process, so as to (1) maximize discriminations; (2) minimize disruptive interference; and (3) promote eventual skill stabilization and integration.

Quite a bit of introspective data will be necessary during cognitive task analyses. It is quite easy to go astray in gathering and interpreting such data (cf. Nisbett and Wilson's [1977] criticism of verbal reports and Ericsson and Simon's [1980] attempt to clarify the issues involved). Introspective analyses have clearly been fruitful nevertheless (see references in Section III to cognitive task analyses under Manipulation of Encoding for Training). The point is that these analyses must be done right if they are to provide guidance for training.

As for other methodologies, ISD provides a suitable framework for viewing task structures vis-à-vis training, provided ISD is used as a general guide for relating cognitive-motor structures to training issues. ISD should not be substituted for an understanding of these structures, nor its prescriptions for a discerning application of what is known regarding discrimination learning.

The research suggested here would develop prototypes of learning analyses that incorporate these various methodologies so as to optimize the design of training programs and equipment. In the process, the skills involved would, of course, be understood sufficiently for immediate implementation of

training, or for the design of training equipment to use in teaching the skills.

NATURE AND PROGRESS OF SKILL INTEGRATION. A key part of the analysis of skill learning is knowledge of the intra- and intertask integrations that occur, how they occur, and when they occur. There has been almost no research on this topic either in the laboratory or in applied contexts. In fact, the work cited above and in Section IV on integration of carrier landing tasks (Isley & Spears, 1982; Isley et al., 1982) has few if any precedents.

Because of the central role of skill integration in performance, there is a need to determine how it develops and factors that affect its acquisition. Such is the research suggested here. The effort could be combined with the development of procedures for learning analyses, and eventually should be because the learning analyses will define clearly not only the tasks to be integrated but the nature of their organization. However, it will take time to complete the learning analyses and implement them in training. Much groundwork could be laid ahead of time through expansions of the analyses of skill integrations as done by Isley and Spears and Isley et al.

Because so little is known regarding how skills are integrated, original research efforts should probably focus on the topological properties of skill organizations, and how topological relations develop with practice. Topological properties refer to those characteristics of information processing that are common to a variety of separate skills. For example, the pilots studied by Isley et al. appeared to have set subgoals in that one component such as angle of attack (AOA) of the carrier approach was first brought into tolerance. Then attention shifted to a second subgoal, say, altitude in tolerance; etc. It is likely that the integration of a large number of skills follows such a pattern of alternating subgoals. Further, topological analyses would likely reveal the establishment of consonance in movement harmonics, development of hierarchical schematic processing (e.g., which is easier, to base altitude control on a maintained AOA or vice versa?), rehearsal strategies for remembering cue matrices and selecting and initiating responses, etc.

As stated in the discussion of the preceding topic, considerable idiosyncrasy can be expected from one performer to another in the details of integrative patterns. Yet, topological properties should be common across performers, and even across at least broad classes of skills. Hence, as with the preceding topic, at least two, preferably three, types of skills should be represented in the study so as to permit common properties to be identified. Depending on the skill, the nature and progress of integration would be sought in the cognitive representations of the component tasks as discussed in Section III, short-term cue processing and experiential (memory) bases for cue interpretations, and/or the coordination of motor actions. Analytic methods would range from introspective analyses by the performers and logical reconstructions of cognitive processes inferred from observed performance, to empirical analyses of what the performer is doing from time to time. However, provisions for empirical analyses should be more systematic than was the case with Isley and his colleagues. Their findings were somewhat a serendipitous "fall out" of another set of analyses. Specifically, a "time-line" is needed against which to plot successive aspects of performance on tasks comprising skills, thereby

making possible more adequate time series analyses. For this reason, early work should probably focus on skill learning using training devices that permit computerized records of performance on each task and subtask along a time dimension.

INTERPRETABLE MANIFESTATIONS OF TRANSFER. Transfer of skill learning from training devices to operational equipment is a critical concern in any device training. It becomes problematic to the extent that the training equipment differs in scope (part-task devices) or is low in fidelity with respect to actual equipment. For this reason, there have been numerous studies of transfer of tasks learned in devices with a variety of characteristics to performance with operational equipment. However, as worthy as these studies have been, almost all fall short in one respect: They focus only on input variables (device characteristics, amount of practice, etc.) and output variables (performance with actual equipment). It should be evident from Sections II-IV that one cannot understand the roles of inputs without allowing for how the information they provide is processed. In brief, there is a need for an empirical methodology that permits assessments of effects of information processing, and hence of training practices and device characteristics that govern desirable processing.

The question is how to design evaluative transfer studies so as to yield data with unambiguous implications for assessments of information processing. For example, Section V illustrates the kinds of inferences that could be made from parameters of performance curves. As was evident, however, unambiguous interpretations call for experimental controls, and/or manipulations of variables during training, that are not now considered in the design of transfer studies.

Building on the examples in Section V, and on the quantitative empirical techniques for isolating signal (cue) detection, speed-accuracy trade-offs, etc., as discussed in Section IV, a general methodology can be readily developed for isolating effects of most processing factors in transfer. The methodologies would incorporate four kinds of considerations: (1) training variables to be manipulated and general rules for the manipulations; (2) variables to be controlled experimentally (or statistically), and/or varied in such a way that their interactions with training variables clarify the effects of the latter; (3) measures of pre- and post-transfer performance that could reveal interpretable effects of training variables; and (4) formulations through equations or otherwise of the measures such as to reveal particular dependencies of performance variables on training variables.

Because of the availability of a variety of data concerning information processing, this research problem would be primarily a logical enterprise. The first step would be to determine how processes discussed in Sections III and IV would affect transfer, positive or negative. Second, empirical indicators of transfer effects would be identified. Third, more than one process are likely to affect some indicators, so factors would be identified such that their control or systematic manipulation would permit unambiguous assessments of separate effects of variables at issue. Fourth, techniques for quantifying and comparing indicators of transfer would be developed (e.g., equations for learning curves, for likelihood ratios, hierarchical scaling, etc.). And fifth, convenient computational and interpretative schemes would be outlined.

INTEGRATION OF RESEARCH. These example topics not only illustrate the variety of worthy research that can be done, they also suggest how topics can be selected for programmatic efforts. A methodology for learning analyses would lead to the design of training programs and equipment; analyses of skill integrative processes would provide criteria for assessing the progression of learning and level of achievement at various stages; a methodology for identifying the roles of processing variables in transfer would reveal specific strengths and weaknesses of the training equipment and the manner of its use. While many other research topics could, and eventually should, be proposed, these three focus on the major phases of any training. They would integrate the design, monitoring, and evaluation of training into a systematic conceptual framework.

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